The spatial distribution of lumbar muscle activity in people with chronic non-specific low back pain

By

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Abstract

Chronic non-specific low back pain (CNSLBP) is the leading global cause of disability, with economic/societal implications. Lumbar muscle activity is investigated as a mechanism to understand the presence and/or persistence of symptoms. High-density electromyography (HDEMG) allows detailed recording of muscle activity across a large region; permitting identification of subtle differences in activation. This thesis consists of five studies. A systematic review identified weak level of evidence for no differences in the magnitude of muscle activity between CNSLBP and healthy populations. However, identified trends supported further investigation of the erector spinae (ES) muscle, and trunk flexion and extension tasks. Three observational studies subsequently used HDEMG to assess ES activity during static, simple monoplanar, and complex multiplanar dynamic tasks. Results identified a less diffuse and more cranially focussed distribution of muscle activity in people experiencing CNSLBP. Finally, an exploratory quasi-experimental study investigated if HDEMG biofeedback could enable people with CNSLBP to activate caudal regions of the ES. Results identified an altered distribution of activity with biofeedback during a dynamic task, but with no changes in pain or exertion. In this thesis, HDEMG recordings identified altered distributions of ES activity in people with CNSLBP, and HDEMG biofeedback may alter this distribution.

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List of Papers and Conference Abstracts

The following papers have either been published, presented in conferences or are in preparation/under review and relate to this thesis directly. A summary will be provided with further detail of the papers and their use within this thesis at the start of each Chapter where required. Therefore, sections of this thesis are written verbatim from published work. Further sections of the thesis have been developed from published work and in this situation will resemble the published work in terms of structure and some content.

Published Articles

Sanderson, A., Cescon, C., Heneghan, N. R., Kuithan, P., Martinez-Valdes, E., Rushton, A., Barbero, M., Falla, D. 2019. People with Low Back Pain Display a Different Distribution of Erector Spinae Activity During a Singular Mono-Planar Lifting Task. *Frontiers in Sports and Active Living*, 1. **(Appendix 1)**

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Sanderson, A., Rushton, A. B., Martinez-Valdes, E., Heneghan, N. R., Gallina, A., Falla, D. 2019. The effect of chronic, non-specific low back pain on superficial lumbar muscle activity: a protocol for a systematic review and meta-analysis. *BMJ Open*, 9, e029850. **(Appendix 3)**

Articles in Preparation

Sanderson, A., Rushton, A. B., Gallina, A., Heneghan, N. R., Falla, D. The effect of chronic, non-specific low back pain on superficial lumbar muscle activity: A Systematic Review. (In Preparation)

Sanderson, A., Cescon, C., Martinez-Valdes, E., Rushton, A., Heneghan, N.R., Barbero, M., Kuithan, P., Falla, D. Reduced variability in erector spinae activity in people with low back pain during a dynamic 3-D lifting task. (In Preparation)

Conference Presentations

Platform Presentations

Sanderson, A., Martinez-Valdes, E., Murillo, C., Heneghan, N.H., Rushton, A., Falla, D. A High-density EMG investigation of changes in erector spinae activity during an endurance task. 2017 Winter Meeting of the Anatomical Society. Dundee, United Kingdom, December 18-20, 2017.

Sanderson, A., Martinez-Valdes, E., Murillo, C., Heneghan, N.H., Rushton, A., Falla, D. People with chronic low back pain show differences in the spatial distribution of erector spinae activity during an endurance task. XXII Congress of the International Society of Electrophysiology and Kinesiology (ISEK). Dublin, Ireland, June 30-2, 2018.

Sanderson, A., Martinez-Valdes, E., Heneghan, N.H., Murillo, C., Rushton, A., Falla, D. Individuals with chronic low back pain demonstrate less diffused muscle activation in the lumbar erector spinae when completing an endurance task. Society for Back Pain Research (SBPR). Groningen, Netherlands, November 15-16, 2018.

Sanderson, A., Cescon, C., Heneghan, N.R., Rushton, A., Barbero, M., Falla, D. What is the Influence of Low Back Pain on Muscle Activity and Movement during a Cyclical Dynamic Task? Pain Science in Motion III (PSIM). Savona, Italy, May 31-2, 2019.

Sanderson, A., Cescon, C., Heneghan, N.R., Rushton, A., Barbero, M., Kuithan, P., Falla, D. How does Low Back Pain Influence Muscle Activity during a Cyclical Dynamic Lifting Task? Physiotherapy UK 2019. Birmingham, UK, 1st – 2nd November 2019.

Poster Presentations

Sanderson, A., Cescon, C., Kuithan, P., Rushton, A., Heneghan, N.R., Barbero, M., Falla, D. Spatial distribution of erector spinae activity in people with low back pain during a dynamic lifting task. 19th Congress of International Federation of the Associations of Anatomists. London, UK, 9th – 11th August 2019.

Upcoming Presentations

Sanderson, A., Cescon, C., Kuithan, P., Rushton, A., Heneghan, N.R., Martinez-Valdes, E., Barbero, M., Falla, D. People with chronic low back pain display an altered distribution of erector spinae activity during a singular mono-planar lifting task. XXIII Congress of the

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ABBREVIATIONS

Acronym	Definition
2-D	Two-dimensional
3-D	Three-dimensional
AMSTAR-2	A MeaSurement Tool to Assess systematic Reviews 2
ANCOVA	Analysis of Co-Variance
ANOVA	Analysis of Variance
AU	Arbitrary Units
BMI	Body Mass Index
C1-C10	Cycle One – Cycle Ten
CD	Critical Domain in the AMSTAR-2
CI	Confidence Interval
CNSLBP	Chronic, Non-Specific Low Back Pain
CON	Control Participant
DASS-21	21 Item Depression Anxiety & Stress Scale
E1-E2	Epoch one – Epoch two
EMG	Electromyography
ES	Erector Spinae
FABQ	Fear Avoidance Beliefs Questionnaire
GRADE	Grading of Recommendations, Assessment, Development and Evaluations
HDEMG	High Density Electromyography
ICC	Intraclass Correlation Co-efficient
IED	Interelectrode Distance
IMU	Inertial Motion Unit
IPAQ	International Physical Activity Questionnaire
L1 – L5	First to Fifth Lumbar Vertebrae
LBP	Low Back Pain Participant

LS	Lumbar Segment
MESH	Medical Subject Heading
MNF	Mean Power Spectral Frequency
MVC	Maximal Voluntary Contraction
NOS	Newcastle-Ottawa Scale
Non-CD	Non-Critical Domain in the AMSTAR-2
ODI	Oswestry Disability Index
PC	Postural Correction
PCS	Pain Catastrophising Scale
PNRS	Pain Numeric Rating Scale
PRISMA-P	Preferred Reporting Items for Systematic Reviews and Meta-Analyses – Protocol
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PROM	Patient Reported Outcome Measure
PSEQ	Pain Self Efficacy Questionnaire
RMS	Root Mean Squared
ROB	Risk of Bias
RVC	Reference Voluntary Contraction
S1-S6	Shelf One- Shelf Six
SF-36	Short Form 36 Item Survey
SF-35 MCS	Short Form 36 Item Survey – Mental Component Scale
SF-36 PCS	Short Form 36 Item Survey – Physical Component Scale
SMVC	Sub-Maximal Voluntary Contraction
STROBE	Strengthening the Reporting of Observational studies in Epidemiology
TS	Thoracic Segment
TSK	Tampa Scale for Kinesiophobia

CHAPTER 1

CHRONIC NON-SPECIFIC LOW BACK PAIN AND LUMBAR MUSCLE FUNCTION

1.1 – Low Back Pain

Globally, chronic non-specific low back pain (CNSLBP) is the leading cause of disability (Hartvigsen et al., 2018, James et al., 2018). It is believed that activity-limiting symptoms of CNSLBP are experienced with a point prevalence of 540 million individuals globally (Hartvigsen et al., 2018). This prevalence of symptoms has ensured that CNSLBP is, and has continuously been, the leading cause of days lived with disability globally since the metric was first recorded in 1997 (James et al., 2018). The collective influence of these years lived with disability places considerable strain on global economies and healthcare providers. In the most recent estimation of costs in UK (2007-2009), the annual direct healthcare costs of CNSLBP were estimated to be £1.5-£2.8 billion; primarily due to people with CNSLBP accruing double the yearly healthcare cost of pain-free individuals (Hong et al., 2013).

1.1.1 – Definition of Terms

CNSLBP is clinically defined by localised pain between the costal margins and the inferior gluteal folds, with or without radiating leg pain (Koes et al., 2006). In some cases (up

to 10%) there is a specific pathological origin for low back pain (*e.g.* tumour, spinal fracture or spondylolisthesis) (de Campos, 2017, Koes et al., 2006). However, in approximately 90% of individuals who experience low back pain there is no specific underlying pathoanatomical cause which can fully explain the appearance of symptoms, these cases are termed 'non-specific' (Koes et al., 2006, Balague et al., 2012). Within the non-specific low back pain population, there is a group who do not experience relief in their symptoms and progress from acute to chronic pain (symptoms lasting >12 weeks) (Balague et al., 2012, Dionne et al., 2008). Henschke et al. (2008) monitored the progression of low back pain symptoms in a socioeconomically diverse group over one year. In this study they noted that after three months only 52% of participants described themselves as 'pain free', a number which rose to 57% after one year from symptom onset (Henschke et al., 2008). The combination of these factors creates the discrete population of interest of CNSLBP, which is the focus of this thesis.

This form of LBP was selected due to the broad clinical challenges associated with CNSLBP management (Foster et al., 2018). In contrast to acute LBP and chronic, specific LBP, participants who experience CNSLBP have neither an expected time frame for symptom easement, nor pathological diagnoses underlying symptoms (Balague et al., 2012). As such, further research in to mechanisms which underlie the perpetuation of symptoms in CNSLBP can help to elucidate and optimise management approaches. Further, a sub-categorisation of CNSLBP is recurrent LBP, defined by sporadic reappearance of symptoms over the course of months or years. The differences and similarities in muscle activity in individuals with persistent CNSLBP and recurrent low back pain is an interesting and much considered area (Tamcan et al., 2010). The key delineation between these types of CNSLBP is that individuals with recurrent CNSLBP have periods of symptom remission experiencing return of their pain; whereas those with persistent pain may have continuous pain with no relief. However there is

little consensus on the definition of 'recurrent' LBP (Stanton et al., 2010), and often studies have used varied criteria to recruit these individuals (Winder et al., 2019, Abboud et al., 2014). Thus, in order to provide consistency, the broad categorisation of persistent CNSLBP was chosen, rather than a somewhat narrower and less defined focus on recurrent LBP.

1.1.2 – CNSLBP Management

Current management of CNSLBP incorporates a biopsychosocial framework, encompassing all elements which may influence the persistence of pain symptoms (NICE Guidelines, 2016, Kamper et al., 2015). This framework recognises the contributions of the biological, psychological and social elements of CNSLBP persistence, and intends that healthcare professionals consider all elements in multi-modal management approaches (Turk and Monarch, 2018). Examples of biological elements include muscle spasm and changes in the activation of muscles (Turk and Monarch, 2018). The psychosocial elements may include anxiety and depression linked to symptoms, and the potential effects that the symptoms may have on an individual's work and social life (Kamper et al., 2015). The individual and combined influence of these factors on a person can be measured using Patient Related Outcome Measures (PROMs). The studies within this thesis will focus primarily on the biological elements of CNSLBP within this framework, with a specific focus on muscle activity. While research in any area within this framework is beneficial, this specific focus was chosen as a continuation of previous work. Prior studies investigating changes in paraspinal muscle activity in people with CNSLBP have identified varied differences muscle activation (Correia et al., 2016, Ershad et al., 2009, Jubany et al., 2017a, Lariviere et al., 2002b). Furthermore, advancement in techniques to understand muscle activation have begun to allow more detailed investigations in

this area (Abboud et al., 2014, Falla et al., 2014); however, further research is needed to fully understand how muscle activity differs in people with CNSLBP, a gap this thesis aims to address.

1.2 – Anatomy of the Lumbar Region

The lumbar region comprises of complex anatomy, which contributes to the structural stability of the upper body (Moore et al., 2013). The anatomical region extends from the first lumbar vertebrae (L1) to the base of the fifth lumbar vertebrae (L5), with lateral borders of the paraspinal region extending to the mid-axillary line laterally (Bogduk, 2005). Passive stability in the region originates from non-contractile tissues, such as the vertebral column and ligaments. However, these structures are functionally supported by active contribution of layers of paraspinal muscles which can generate movement, or stabilise the spine during upper-body activities.

The main paraspinal muscles comprise of the *erector spinae* (ES) and the *multifidus* muscles bilaterally which produce all lumbar functional movements (Fig. 1.1). There are also smaller and deeper muscles such as the *quadratus lumborum* and *interspinalis* muscles, however these muscles primarily function to provide stability in the region rather than create movement. The ES is comprised of three constituent parts, the *iliocostalis, longissimus* and *spinalis*, which in turn are subdivided into smaller functional regions (Bogduk, 2005, Ebraheim et al., 2004, Hodges and Danneels, 2019). Across ES, the distribution of the muscle fibres of the *spinalis* is focussed in the thoracic and lower cervical regions, and as such is considered to not be present in the lumbar region (Ebraheim et al., 2004). Within the lumbar region, the primary constituent parts of ES are the *iliocostalis lumborum* and the *longissimus thoracis*. These muscles are further divided, with regions of each muscle arising from the lumbar and

thoracic regions; distinguished by the suffixes *-pars lumborum* or *-pars thoracis* (Bogduk, 1980, Bogduk, 2005, Hodges and Danneels, 2019, Macintosh and Bogduk, 1991). The *multifidus* lies medially to the ES components and is located at the caudal end of the vertebral column, occupying the region immediately lateral to the spinous process (Hodges and Danneels, 2019, Rosatelli et al., 2008). The approximate locations and distributions of these muscle are summarised in Fig. 1.1.

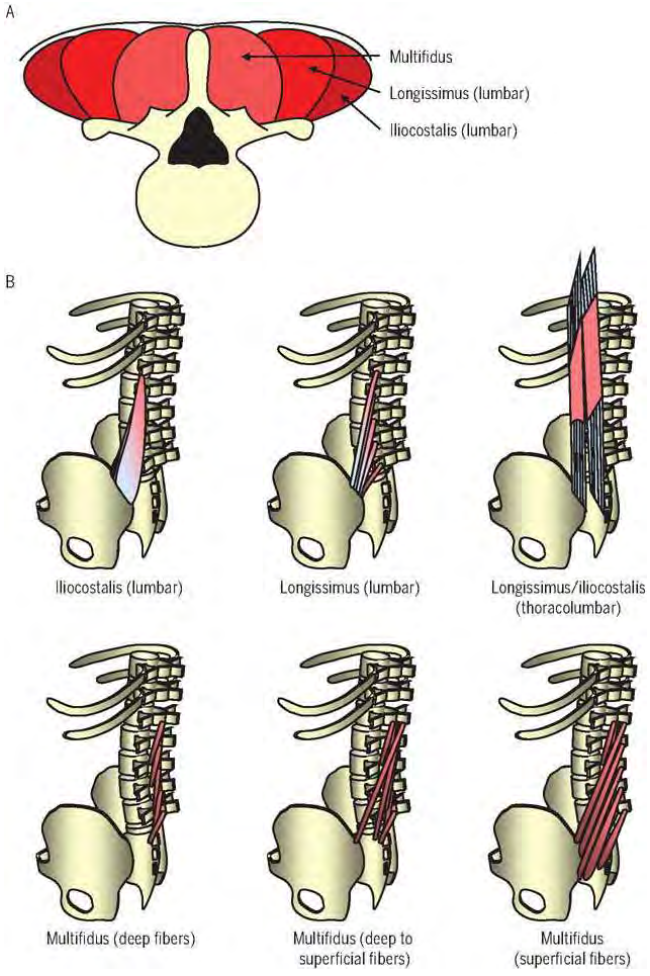


Fig. 1.1 – Illustrating the anatomical structure of the lumbar paraspinal muscles in (A) a cross sectional view and (B) *in situ* with a focus on fibre orientation. The bracketed region denotes the muscle fibre origin and is synonymous with pars region. Reproduced

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There are several studies which have investigated the detailed anatomy of the lumbar region in cadaveric specimens (Bogduk, 1980, Bustami, 1986, Macintosh and Bogduk, 1991, Rosatelli et al., 2008). The structure of the *multifidus* is well described, with deep and superficial components forming the gross morphology, and all fibres lying in close proximity to the lumbar spinous processes (Rosatelli et al., 2008). The deep fibres lie adjacent to the spinous process, originating from the base of a spinous process and inserting into the mammillary processes two levels caudally. The superficial *multifidus* fibres extend from the tip of the lumbar spinous processes to mammillary processes four levels caudally, with insertions on L5 and the sacrum (Rosatelli et al., 2008).

The structure of the ES is more complex, with differing structures for the *pars lumborum* and *pars thoracis* regions of each muscle. The *pars lumborum* of each muscle comprises of relatively short fibres extending from the pelvis to each lumbar vertebra. The *longissimus thoracis pars lumborum* is the most medial region, closest to the spinous processes, and deep to the slightly more lateral and superficial *iliocostalis lumborum pars lumborum* (Bogduk, 2005, Hodges and Danneels, 2019). The *longissimus thoracis pars lumborum* has a laminated appearance with partially overlapping lamina to each vertebra. The deepest and most medial fibres extend from the dorsal transverse process of the L5 vertebrae to the posterior superior iliac spine, and each consecutive vertebral fascicle lies more superficially and medially (Bogduk, 2005, Macintosh and Bogduk, 1991). The *iliocostalis lumborum pars lumborum* comprises of an opposing arrangement of fibres, lying more laterally and extending between the tip of the transverse processes of L1-L4 to the posterior iliac spine. In this instance, the most superficial and medial fibres are those to L1, and fascicles to each successive vertebrae lie deeper and more lateral (Bogduk, 2005).

The fibres from the *pars thoracis* of each of these muscles extend between the thoracic region and insert caudally on the sacrum, with primarily tendinous regions overlying the lumbar ES regions (Bogduk, 1980, Bogduk, 2005). The *longissimus thoracis pars thoracis* lies medially, but no longer deep to the lateral *iliocostalis lumborum pars thoracis*, creating a banded appearance (Fig. 1.1) (Hodges and Danneels, 2019, Macintosh and Bogduk, 1991). The medial *longissimus thoracis pars thoracis* fascicles arise from the thoracic transverse processes, and extend caudally, inserting between L1 and the sacrum. Laterally, arising from the costal angles of the ribs, the body of the *iliocostalis lumborum pars thoracis* extends to the iliac crest, 5cm lateral to the posterior superior iliac spine (Macintosh and Bogduk, 1991).

1.2.1 – Functional Anatomy and CNSLBP

In vivo, biomechanical modelling is used to understand the exact functional contributions of the muscle regions previously described to create movement (Christophy et al., 2012, Daggfeldt and Thorstensson, 2003, Sieben et al., 2016). Recent studies which have investigated the functional contributions of the ES and the *multifidus*, have identified differences in the primary function of each muscle. The shorter fibres and greater cross-sectional area of the *multifidus* are believed to contribute to spinal stability above the creation of functional movement (Mawston and Boocock, 2015). Conversely, while this is less well understood at a gross level, it is widely considered that the ES, as well as contributing to the stability of the spine and the structure of the lumbar lordosis, primarily contributes to creating functional movements (Christophy et al., 2012, Daggfeldt and Thorstensson, 2003, Mawston and Boocock, 2015). The biomechanical basis of this functional difference is considered in the review by Mawston and Boocock (2015), and it is postulated that the long lever arm of the ES

allows for contributions to more functional movements. Specifically, the ES is known to contribute to concentric extension, eccentric flexion, and both concentric and eccentric axial rotation and lateral flexion within functional movements (Lee et al., 2005, Shojaei et al., 2017b). This distinction in function is important, as people who experience CNSLBP commonly report exacerbation in symptoms related to functional movements (Hanney et al., 2013), therefore the focus of the work in this thesis focuses on the ES which primarily underlies these functional movements.

However, in the presence of CNSLBP, it is thought that both the ES and the *multifidus* and the abdominal flexors may function differently, creating abnormal movement patterns which could be a contributing factor in the persistence of symptoms (Hemming et al., 2018, Hodges and Danneels, 2019). It is thought that many factors may underlie changes in the functional anatomy in the lumbar region, for example authors have investigated changes in the macroscopic and gross biomechanical properties of the constituent tissues (*e.g.* increased stiffness or altered vertebral kinematics) (Breen et al., 2018, Murillo et al., 2019a, Hemming et al., 2018). Thus, as contractile tissue in the region which creates and controls movement, the lumbar paraspinal muscles are often investigated as a mechanism underlying biomechanical changes in people with CNSLBP (Goubert et al., 2017, Hodges and Danneels, 2019, Mannion et al., 2000, Rissanen, 2004). Additionally, the lumbar ES is a large and subcutaneous muscle which facilitates investigation through surface techniques as described later in this thesis. Thus, due to the perceived role of the lumbar ES as a functional muscle; and the subcutaneous distribution of fibres; this thesis will focus on the activity of the ES during functional movements.

1.3 – Low Back Pain and Movement

In addition to the pain and disability experienced by people with CNSLBP, it has also been shown that people with CNSLBP use altered movement strategies (van Dieen et al., 2018). These altered movement strategies centre around the concept that people with CNSLBP modify their movement to avoid exacerbation of their symptoms (Hodges and Tucker, 2011, Peck et al., 2008). However, more recent studies have identified that these adaptations often contribute secondary consequences which cause more pain and further adaptations to avoid exacerbation of symptoms (van Dieen et al., 2017). This pattern of adaptation and secondary consequences is termed the 'vicious cycle' whereby pain begets further pain (O'Sullivan et al., 2018). As such, understanding the ways in which people with CNSLBP produce movement, and abnormalities therein, is a promising area of research and may offer novel approaches to support rehabilitation.

1.3.1 – Techniques for Quantifying Changes in Paraspinal Muscle Function

As the purpose of a muscle is to produce or control movement (Palastanga et al., 2013), muscle function can be defined as the ability of the contractile tissue or region to produce or control effective movement. From a research perspective, this can be investigated at two levels, (1) the gross level of the movement produced, termed kinematics, or (2) the macroscopic level of the muscle contraction underlying the movement. Studies have previously shown that while these two factors are related, they are not directly correlated and there is merit in assessing both (Mauntel et al., 2018, Schrijvers et al., 2019).

Kinematic analysis refers to the practice of capturing the three-dimensional (3-D) pattern of a movement, in order to quantify parameters including the speed, duration, angular momentum and range of motion of a movement in space (Gatton and Pearcy, 1999, Williams et al., 2013b). Within the lumbar region, these outcomes have been investigated in gait, lifting tasks, rowing and back-specific movements such as lumbar extensions to identify differences in 3-D motion both in people with and without CNSLBP (Hemming et al., 2018, Thurston and Harris, 1983, Johnson, 2017, Fujii et al., 2007) As such, 3-D kinematics have been explored extensively in people with CNSLBP (Arjmand and Shirazi-Adl, 2005, Cholewicki et al., 2019, Gomez, 1994, Graham et al., 2014, Hemming et al., 2018, Sung, 2014, van Andel et al., 2008), but this technique can also be used to facilitate comparisons of other outcomes.

1.4 – Electromyography and Muscle Activity

Muscle activity can be identified and recorded using electromyography (EMG) (Merletti and Farina, 2016), and can be used to assess the magnitude, duration and distribution of muscle activation, in addition to detailed investigations of individual motor units (Del Vecchio et al., 2017, Merletti and Farina, 2016). EMG allows quantification of the electrical activity released to initiate a muscle contraction, this release of activity is the culmination of complex neuromuscular processes underpinning volitional movement (Konrad, 2006). When a movement is initiated at a cortical level, an impulse is transmitted via somatic efferent nerves (motoneurons) to a target muscle to initiate contraction. At a macroscopic level, each motoneuron innervates selected fibres within a muscle; the combination of a single motoneuron and the muscle fibres it innervates is termed a motor unit (Del Vecchio et al., 2017).

1.4.1 – Measurement of Muscle Activity

EMG is utilised to measure the difference in the electrical activity released by a muscle contraction using electrical sensors (electrodes). Two techniques are widely utilised to enable this, intramuscular and surface EMG. Intramuscular EMG involves insertion of a finewire or needle electrode into the muscle belly and activity is measured with the electrode *in situ*. The second technique, which is used within this thesis, is surface EMG where electrodes are applied to the surface of the skin overlying the muscle of interest (Merletti and Farina, 2016, Jiang et al., 2010). Surface EMG was focussed on here due to ease of use; it is a non-invasive technique which can be used clinically with relative ease compared to the more invasive and aseptic conditions required for intramuscular EMG (Jiang et al., 2010).

The traditional surface EMG experimental design includes a pair of electrodes which are placed over the belly of the muscle, and a further reference electrode placed over a non-contractile region (Fig. 1.2). The reference electrode allows a measure of a baseline activity, with no contraction-based fluctuations in the electrical activity, thus providing a reference value for electrical conductance of the skin and to enable comparison with the electrical activity of the contraction (Merletti and Farina, 2016). The pair of electrodes over the muscle belly are termed 'bipolar' for the negative and positive electrodes within the arrangement. These bipolar electrodes are placed at a fixed distance apart [inter-electrode distance (IED)] and positioned to match the fibre orientation below the skin; to record the signal as it propagates along the fibre (Barbero et al., 2012). Adherence to specific guidelines for electrode placement improve the reliability of EMG measurements between studies and ensure that signals are recorded from optimal locations (Hermens et al., 2000, Barbero et al., 2012, Beretta Piccoli et al., 2014, Boccia and Rainoldi, 2014, Criswell, 2010). Following electrode placement, the electrical potential is recorded from the sensors at a designated sampling frequency, and the resultant signals are

amplified to magnify the myoelectrical signal and filter electrical noise (Merletti and Farina, 2016, Tankisi et al., 2020).

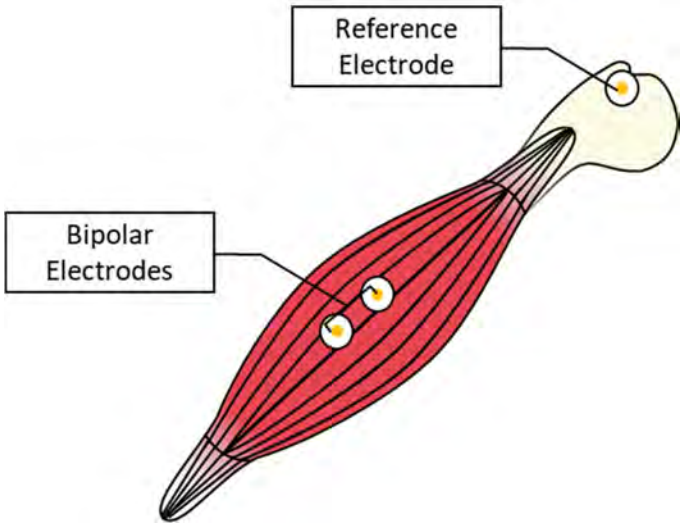


Fig. 1.2 – Bipolar electrode placement over the muscle belly. In this instance the skin is not shown for the sake of clarity, however these electrodes would be placed on the skin overlying the muscle in this position (not to scale).

Technological advances have led to the development of two-dimensional (2-D) arrays of multiple electrodes; termed high-density electromyography (HDEMG). These arrays facilitate detailed investigation of activity within a muscle, and the identification of regional differences (Gallina et al., 2013, Hodges, 2014, Afsharipour et al., 2019, Drost et al., 2006). Using HDEMG grids of smaller single electrodes, tens to hundreds of signals can be measured over a relatively small area (Fig. 1.3). This approach allows identification of more subtle differences in muscle activity rather than the singular outcome derived from bipolar sensors. Instead, the equivalent information is extracted from each electrode, conveying important topographical differences in the distribution of activity across the surface of a muscle (Afsharipour et al., 2019, Drost et al., 2006, Gallina et al., 2013). A recent review by Falla and Gallina (2020), demonstrated how HDEMG has been used to identify this more subtle change

in the muscle activation, identifying major differences in the distribution of muscle activity in pain.

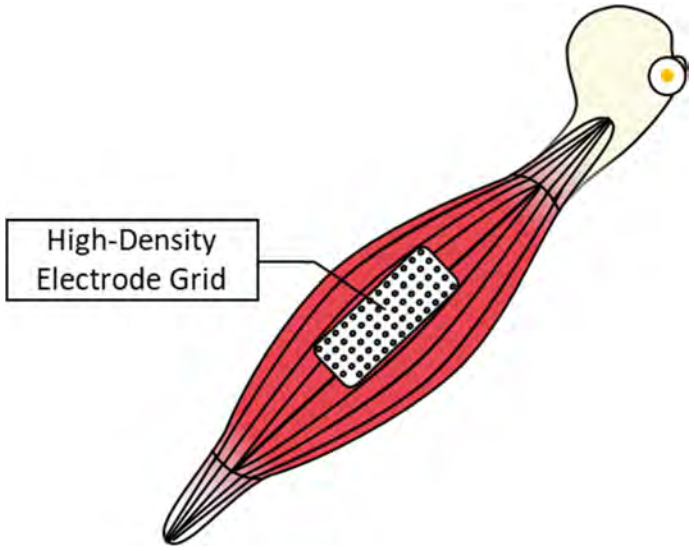


Fig. 1.3 – Depicting the placement of a 64 channel HDEMG electrode grid over the muscle belly. In this instance the skin is not shown for the sake of clarity, however this grid would be placed on the skin overlying the min this position (not to scale).

1.4.2 – Muscle Activity Outcomes

Following the recording of EMG or HDEMG signals, the data from individual signals are processed to derive interpretable outcomes from the amplitude and frequency of signals. The amplitude of the signal, and changes therein across time, are used to determine the level of activity in the muscle. These data are typically processed into the root mean amplitude squared (RMS) deriving the square root of the mean amplitude squared, which eliminates negative values to ensure that positive and negative components of the signal do not cancel each other out (Merletti and Farina, 2016). Using HDEMG, these RMS values can be plotted topographically in the arrangement of electrodes within the grid. This arrangement of amplitude

values can provide a weighted value for the centre of the contraction (centroid), determined by the spatial distribution of RMS values. This centroid can be further dissembled into an X- and Y-barycentre, representing the position of the centroid in the X (medio-lateral) and Y (cranio-caudal) axes (Fig. 1.4) (Barbero et al., 2016, Gallina et al., 2013, Madeleine et al., 2006). The centroid of the EMG amplitude map is unique to each participant and is plotted as a 2-dimensional coordinate based on the distribution of the EMG amplitude across the grid. As a calculated measure, the centroid location is typically reported as a group average to the 100^{th} of a millimetre, however further work is required to investigate if shifts of less than 1mm are meaningful (Tucker et al., 2009). The RMS of signals can also be processed to derive a measure of entropy across an electrode grid, or an arrangement of bipolar electrodes. Entropy is a measure of the uniformity of signals, with more homogeneous activation across the arrangement resulting in greater entropy values (Farina et al., 2008). The measure of entropy uses arbitrary units (AU), so the minimum magnitude of a meaningful change is not currently known. However, a recent review by Rampichini et al. (2020), considered entropy measurements pre- and post-fatiguing exercise and identified reported differences between conditions of 0.1-0.6AU across all considered studies so changes in this outcome are typically small. Finally, the frequency of the signal can be used to derive the myoelectric manifestations of fatigue, whereby a decrease in the frequency indicates an increase in myoelectric fatigue (Merletti et al., 1990, Farina et al., 2014). It is important to note that myoelectric fatigue does not identify the point of task failure, it is instead a continuous measure of the decline in the ability of a muscle to produce maximal force and/or power (Enoka and Duchateau, 2008).

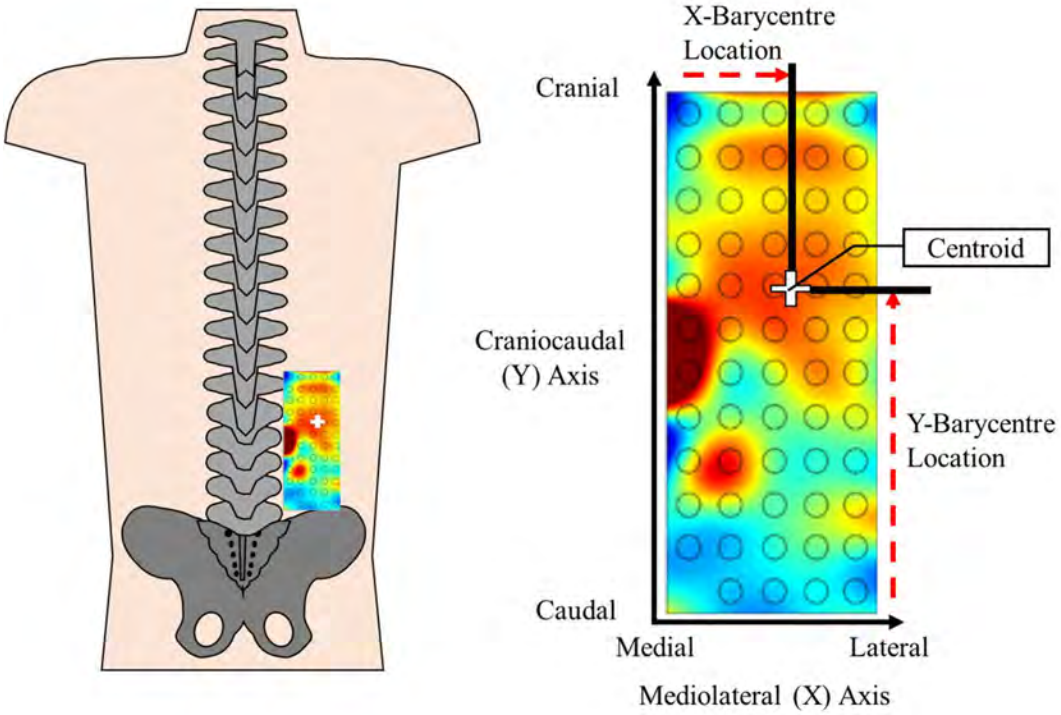


Fig. 1.4 – (A) a depiction of the topographical map over the trunk and (B) the axes and measurement properties of the centroid of the EMG amplitude map and independent characterisations of the X- and Y-barycentre's in their respective axes.

1.4.3 – Factors which can affect EMG

As previously described, surface EMG is a cutaneous technique used to measure muscle activity from subcutaneous muscle tissue. As such, intrinsic structures beneath the skin can affect the signal characteristics and must be considered and controlled when using the technique (Raez et al., 2006). The first of these structures is the muscle tissue itself. The neurophysiological contractile signal propagates from the innervation zone as a depolarisation of the fibre (Criswell, 2010). This depolarisation is the signal, which is recorded by EMG, and as such, studies have shown that signals are recorded more accurately if electrodes are placed along the muscle fibre (Merletti et al., 2003, Beretta Piccoli et al., 2014, Boccia and Rainoldi, 2014). Thus, it is important to know the direction of muscle fibres within the target muscle to

ensure that the recording is as accurate as possible. Furthermore, it is likely that adjacent muscles may also be active to produce a gross coordinated movement. As such, exact positioning of the electrodes is important to reduce the effect of 'cross-talk' and ensure that signals are from the muscle of interest (Solomonow et al., 1994). Secondly, the biological tissue between the muscle and the skin can influence the impedance and alter the signal characteristics. In particular, subcutaneous fat is a commonly identified as a factor which can increase the bioimpedance (Nordander et al., 2003, Kuiken et al., 2003). A study by Nordander et al. (2003) identified that the subcutaneous fat layer between muscle and skin could explain between 21-33% of variance in surface EMG signals, with a negative correlation between the distance between the skin to muscle and the EMG amplitude measure. Furthermore, the study by Solomonow et al. (1994) also identified that crosstalk was increased during bipolar recordings in instances where there was a significant layer of subcutaneous fat. However, recent research has also indicated that the combined small electrode diameter and IED increases the specificity of recordings by limiting the detection volume to the surrounding muscle fibres (Vieira et al., 2017). Nonetheless, these studies and limitations highlight the importance of controlling for electrode position, and participants anthropomorphic characteristic (e.g. BMI) when conducting studies using this technique.

The signals can also be affected by extrinsic factors which are more difficult to control for and as such must be acknowledged as a limitation of the technique, for example anthropometric differences and skin movement. As a cutaneous technique, surface EMG and HDEMG are affected by the relative locations of the skin and the underlying tissue, factors which can cause particular difficulties during dynamic movements (Felici and Del Vecchio, 2020). It is recommended to use a uniform IED to achieve the most reliable surface EMG and HDEMG signals (Afsharipour et al., 2019). In HDEMG, this issue is overcome by using semi-

rigid grids of electrodes which are a constant shape and size with fixed IEDs. When applying this technique in the context of CNSLBP, the electrode grids are placed on the participants' lumbar region guided by an anatomical landmark (Abboud et al., 2014, Falla et al., 2014). However, as a result of the fixed grid dimensions the length of the participants trunk will affect how much of the lumbar musculature is covered by electrodes. As such, very tall participants and very small participants may have up to 1-2 vertebral levels difference in the area covered by the grid. This limitation can be minimised by using recommended electrode placements (Criswell, 2010, Barbero et al., 2012, Beretta Piccoli et al., 2014), however the varied distance between these landmarks must be accepted as a limitation of the technique.

A second extrinsic limitation relates to the utility of the technique to record muscle activation during dynamic tasks. The purpose of EMG is to record muscle activity during a contraction; however, with isotonic contractions which create functional movements the underlying muscle fibres will change in length and creating movement of the skin (Felici and Del Vecchio, 2020). As a result, skin movement can occur, whereby the skin which the electrode is adhered to shifts slightly and no longer retains the same relationship with the underlying muscle tissue (Elsais et al., 2020). The magnitude of this shift has been shown to vary between individuals and in bipolar EMG studies the use of ultrasound has been shown to reduce the impact of skin movement on signals (Elsais et al., 2020). No similar investigation has been completed for HDEMG so potential skin movement must be considered as a limitation of the technique.

1.4.4 – Reliability

Reliability is an estimated quantification of the consistency and repeatability of data collected using a given technique, taking into account both systematic and random errors (Bruton et al., 2000). There are two primary categories, relative reliability and absolute reliability; the former being a measure of the repeatability of results of a single individual, and the latter a consideration of the measurement variability between individuals (Bruton et al., 2000, Portney and Watkins, 2009, Sim and Wright, 2005). Validity is a closely connected concept, as it defines the extent to which the measurement technique is accurate in its measurement, in this instance referring to how accurate HDEMG is at measuring muscle activity. As such, it is not possible to fully assess all aspects of validity without first identifying the reliability of the instrument (Mokkink et al., 2018).

Reliability can be reported and interpreted from the intraclass correlation coefficient (ICC; including model when reported) and the corresponding 95% confidence intervals (95% CI) (Sim and Wright, 2005, Portney and Watkins, 2009), with ICCs interpreted in line with guidance from Koo and Li (2016): <0.5 ‘poor’, 0.51-0.75 ‘moderate’, 0.76-0.90 ‘good’ and 0.91-1 ‘excellent reliability’. This measure was considered above other psychometric outcomes as reliability considers both the correlation between reviewers and the repeatability of the measure (Koo and Li, 2016). Consideration of either of these outcomes alone (*e.g.* correlation) could represent similarity without repeatability or vice versa.

1.4.4.1 – Surface EMG Reliability

As a relatively novel technique, reliability data on HDEMG is somewhat scarce, however more reliability research has been conducted on bipolar EMG. This research has identified moderate reliability for measuring muscle activity in the ES in controlled conditions

with appropriate methodological rigor (Afsharipour et al., 2019, Brandt et al., 2017, Kilby et al., 2016, Roy et al., 2007). Several studies have assessed the reliability of bipolar ES recordings during a range of dynamic tasks, identifying good to excellent reliability (Brandt et al., 2017, Schinkel-Ivy et al., 2015). For the lumbar and thoracolumbar ES, ICC values were found between 0.82-0.95 (good – excellent reliability) during flexion and axial rotation for different numbers of trials and regions of the ES (Schinkel-Ivy et al., 2015), and $ICC_{3\text{-}K}$ 0.81 (95% CI 0.75, 0.86) – 0.85 (95% CI 0.82, 0.89) (moderate-good reliability) (Brandt et al., 2017).

Furthermore, a number of studies have specifically investigated reliability in bipolar EMG recordings on the ES in populations with CNSLBP and other types of LBP (Dankaerts et al., 2004, Ahern et al., 1986, Pitcher et al., 2007). The work by Dankaerts et al. (2004) compared the reliability of bipolar EMG recordings of the trunk musculature during isometric contractions in individuals with CNSLBP and healthy controls. In this study, the authors identified good to excellent reliability for the CNSLBP group for both within-day measurements (ICCs between 0.88-0.93 across movements), and between-days measurements (ICCS between 0.76-0.91). There were no 95% CI's reported for this study so it is more difficult to directly compare it to other studies. Similarly, a later study by Pitcher et al. (2007) also reported ICC and range in LBP and control groups across the trunk musculature. This study identified a mean value for the ICC in the LBP group of 0.7 (range 0.36-0.94) across the trunk musculature indicating a large range. The work by Ahern et al. (1986) also reported within session correlations in a LBP population of between 0.66-0.97, with a greater range for between days (0.26-0.92). However, while the authors interpreted these results in accordance with the reliability of the measure, as stated previously, correlation alone is not a good indicator of reliability.

1.4.4.2 – HDEMG Reliability

Where the reliability of HDEMG electrodes has been investigated, these studies have been focussed on the lower limb and within healthy populations. Gallina et al. (2016) identified moderate to excellent reliability of HDEMG recordings for the amplitude of each individual signal ($ICC_{1,10}$ – 0.60, 0.91), and collectively all signals over the *triceps surae* ($ICC_{1,10}$ – 0.73, 0.95). Furthermore, studies have shown that HDEMG can be used to track motor units across several weeks in the *vastus lateralis* and *vastus medialis* muscles, requiring the consistent identification of motor unit characteristics including amplitude and frequency (Martinez-Valdes et al., 2017). Thus, reliability in the tracking of motor units confers reliability on those characteristics used to identify motor units. In this study, approximately 40% of units could be tracked across two weeks with moderate to excellent reliability ($ICC_{2,1}$ – 0.63, 0.99). In a different study, a range of motor unit characteristics were tracked over three sessions in the *vastus lateralis* and *vastus medialis* muscles, with good to excellent reliability demonstrated for 19/25 outcomes ($ICC_{2,1}$ values of 0.75 or greater) (Martinez-Valdes et al., 2016). It is noted however that there is a relative dearth of studies which have assessed both the reliability of HDEMG and the individual outcomes, indicating an area which requires further research. Furthermore, it is noted that these studies, which have been considered do not estimate reliability in the lower back, or in a population who are experiencing chronic pain. While bipolar EMG studies have shown no differences in reliability between individuals with and without LBP (Dankaerts et al., 2004); and indeed, suggested a trend towards greater reliability in the ES activity in individuals with LBP, it is currently not possible to infer reliability of HDEMG in this region or population from these results.

Reliability in the HDEMG specific outcome of the centroid location and the movement of the centroid has not been well assessed in terms of reliability. However, this measure is

commonly used, with expert use offering face validity and a recent review highlighting the use and promising results of this outcome (Falla and Gallina, 2020). Previous studies have assessed the specificity of this measurement, and compared the surface distribution of muscle activity to intramuscular activation (Vieira et al., 2017), and to known subcutaneous anatomical structures (*e.g.* contractive vs non-contractile regions) (Gallina et al., 2013). These studies identified that the distribution of activation recorded from surface HDEMG electrodes is reflective of the regional activation in the muscle; with the area of greatest activation underlying the area with the greatest surface amplitude of signals (Gallina et al., 2013, Vieira et al., 2017).

Furthermore, one study has identified 'moderate to strong' correlations in the centroid location and distribution of activity between sessions (Abboud et al., 2015), using guidelines for interpretation of Pearson correlation coefficients from Evans (1996) (*0.00-0.19, "very weak"; 0.20-0.39, "weak"; 0.40-0.59, "moderate"; 0.60-0.79, "strong"; 0.80-1.0, "very strong"*; pp624). This study assessed the test-retest reliability of the centroid during a fatiguing task and the results are summarised in Table 1.1 (Abboud et al., 2015). Moderate to strong correlations were identified in most outcomes in this study, with more consistently correlated results identified for the centroid location. The dispersion showed fewer correlations initially during phase two and three; however, this effect appears to be stronger both initially, and as the task proceeds (Abboud et al., 2015).

Outcome	Side	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Dispersion	L	**0.46**	0.31	**0.61**	**0.73**	**0.56**	**0.9**
	R	**0.53**	0.31	0.18	**0.65**	**0.53**	**0.92**
Dispersion X-axis	L	**0.51**	0.35	**0.59**	**0.49**	**0.56**	**0.77**
	R	**0.55**	**0.39**	**0.45**	**0.73**	**0.52**	**0.85**
Dispersion Y-axis	L	0.35	**0.47**	0.29	**0.64**	**0.55**	**0.89**
	R	**0.47**	0.3	0.04	**0.56**	**0.43**	**0.79**
Centroid Location X-axis	L	**0.71**	**0.65**	**0.51**	**0.48**	**0.45**	0.22
	R	**0.72**	**0.72**	**0.65**	**0.66**	**0.64**	**0.63**
Centroid Location	L	**0.84**	**0.83**	**0.81**	**0.85**	**0.83**	**0.84**

X-axis	R	**0.87**	**0.87**	**0.87**	**0.86**	**0.84**	**0.83**

Table 1.1 – Bilateral Pearson correlation scores in centroid location and movement across six phases of an endurance task, values in bold represent a significant correlation. Reproduced from Abboud et al. (2015), with permission from Elsevier.

It is evident from the work discussed here, that evidence to support reliability of HDEMG as a measure of muscle activity in the lumbar ES, or indeed in populations with CNSLBP is lacking. In fact, on the contrary there appears to be no studies which have systematically assessed the reliability of the technique in this population or muscle. As such, results of HDEMG on the lumbar ES and/or in a CNSLBP population must be interpreted with caution. in. In order to support the use of this technique within this thesis, it is important that all factors which have been shown to affect measures of muscle activity in EMG and HDEMG are controlled.

1.4.4.3 – Considerations for Reliability

While reliability data are limited in this technique, as discussed in section 1.4.3 there are limitations of EMG which can be controlled to ensure the technique is performed optimally. Electrode grids and placement are two areas which can influence the quality and so the reliability of data. Typically, the grids which are used are semi-rigid and have uniform electrode sizes and a constant inter-electrode distance (Besomi et al., 2019), two factors which if not controlled have been shown to affect HDEMG results (Afsharipour et al., 2019, Kilby et al., 2016). It has also been shown that where errors could occur due to electrodes becoming loose (Roy et al., 2007), steps could be taken to ensure good contact was maintained throughout a task such as using adhesive foam and tape to ensure good contact (Lapatki et al., 2004). There are currently no electrode placement guidelines in operation which have been specifically created for HDEMG. However, as described previously, within the lumbar paraspinal region

several examples of placement guidelines for bipolar systems have been created (Criswell, 2010, Hermens et al., 2000, Barbero et al., 2012), with use of these guidelines identifying greater correlations between intramuscular and surface EMG results for recordings overlying the ES than the *multifidus* (Stokes et al., 2003). As such, the experiments within this thesis have adapted these bipolar guidelines for HDEMG measurement of the ES. Finally, as subcutaneous fat has been shown to influence the amplitude of recorded signals; participants should be matched on BMI. Furthermore, as amplitude is directly affected, the results collected for amplitude should undergo normalisation when possible to reduce the potential for errors between participants caused by differences in subcutaneous fat (Kuiken et al., 2003).

1.5 – Low Back Pain and Surface Electromyography

As discussed previously, the definition of CNSLBP is in itself a diagnosis of chronic LBP which cannot be linked to any definitive pathology or underlying cause. Multidisciplinary biopsychosocial rehabilitation is more effective for reducing LBP symptoms than usual care (moderate quality evidence) or physical therapy alone (low quality evidence) (Kamper et al., 2015). The success of this form of combined rehabilitation relies on strength of rehabilitative practice in each of the constituent biological, psychological and social portions. However, the non-specific diagnosis precludes targeted biological rehabilitation as the mechanism remains unknown. As a result, investigations into the underlying biological mechanisms focus on identifying altered function in non-pathological structures, for example via surface EMG.

One way in which this can be achieved is by investigating activity in the abdominal musculature, such as the *internal oblique* and *external oblique* muscles (Hemming et al., 2019, Kim et al., 2017, Shamsi et al., 2020). However, these studies have presented mixed results, which could be due in part to the difficulty in assessing abdominal muscle activity by surface

EMG techniques. As previously discussed in section 1.4.3, EMG signals can be affected by factors such as subcutaneous fat and cross-talk. As the abdominal region is a key site of subcutaneous fat deposits (Kanehisa et al., 2004), and the musculature is comprised of overlapping layers of muscles (Grevious et al., 2006), it follows that muscle activity signals here might be influenced by these factors.

Previous work has also considered the function of the paraspinal musculature. Numerous studies have investigated the activity of the lumbar paraspinal muscles in people with CNSLBP on muscle activity across a variety of tasks and conditions with bipolar and HDEMG (Demoulin et al., 2007, Drost et al., 2006, Ehsani et al., 2017, Marshall and Murphy, 2008, Russo et al., 2018). While studies using both bipolar and HDEMG have identified differences in CNSLBP, there is no consensus on the influence of CNSLBP on the magnitude of muscle activity.

Studies have also utilised HDEMG to assess lumbar paraspinal muscle activity in people with CNSLBP. Due to the small surface distribution of the lumbar *multifidus* fibres and the relatively large size of the most common HDEMG grids, it is extremely difficult to isolate the *multifidus* from the surface footprint of the ES (Hermens et al., 2000). As such, studies which have employed HDEMG in the paraspinal region have assessed the lumbar ES. Abboud et al. (2014) investigated the dispersion and movement of the centroid within the ES during a Sørenson endurance task. In this study, the authors identified a lower redistribution of muscle activity in people with CNSLBP. A similar result was identified in a study investigating dynamic lifting by Falla et al. (2014). In this instance differences were only identified in the overall muscle activity across the grid at the end of the task, however throughout the task people with CNSLBP demonstrated less redistribution of activity within the muscle. Recently, the distribution of activity in elite rowers with CNSLBP was quantified during ergometer rowing

with increasing load (Martinez-Valdes et al., 2019). In this study, people with CNSLBP exhibited greater levels of muscle activity and less diffuse activation across the lumbar region. Furthermore, muscle activity was shown to redistribute in an opposing manner to pain-free controls (cranial vs caudal redistribution), suggesting the use of an inefficient motor strategy (Martinez-Valdes et al., 2019).

These combined results present evidence to suggest that people with CNSLBP appear to use altered motor control strategies involving aberrant patterns of ES activity to complete functional tasks. However, the exact nature of these differences in people with CNSLBP, including the overall distribution of activity during functional tasks, remains unclear and warrants further investigation.

1.6 – Thesis Aims

This thesis presents a series of studies, which examine changes in lumbar ES in the presence of CNSLBP. The research has been informed by neurophysiological, kinematic and anatomical research. The aim of this thesis was to identify and describe how ES activity differs in the presence of CNSLBP during functional tasks, and more specifically the distribution of activity within the lumbar ES.

1.6.1 – Objectives

The objectives of this thesis have been separated by Chapter and are to;

Chapter 2. Systematically evaluate what differences are present in the magnitude of activity of the superficial lumbar paraspinal musculature during functional back-specific tasks in people with CNSLBP compared to healthy controls.

Chapter 3. Investigate the spatial distribution, and redistribution, of unilateral lumbar ES activity in people with CNSLBP and pain-free controls during a static trunk extension task.

Chapter 4. Investigate the spatial distribution, and redistribution, of bilateral lumbar and thoracolumbar ES activity in people with CNSLBP and pain-free controls during a singular monoplanar lifting task.

Chapter 5. Investigate the spatial distribution, and redistribution, of bilateral lumbar and thoracolumbar ES activity in people with CNSLBP and pain-free controls during a complex multiplanar functional lifting task and identify any differences in the 3-D movement strategy

Chapter 6. The objective of this prospective study was to explore the use of HDEMG biofeedback maps of lumbar and thoracolumbar ES activity to facilitate the activation of caudal regions of the ES in CNSLBP participants and further to investigate the immediate influence of this biofeedback on PROMs.

CHAPTER 2

THE EFFECT OF CHRONIC, NON-SPECIFIC LOW BACK PAIN ON SUPERFICIAL LUMBAR MUSCLE ACTIVITY: A SYSTEMATIC REVIEW

The protocol for this systematic review has been published (Sanderson et al., 2019c); and the methodology of this Chapter largely reflects this verbatim. However, for the purposes of this thesis some elements have been re-worded, including substantial increases to rationale for the choice of risk of bias tool and minor amendments made in the exclusion criteria.

Publication

1. **Sanderson, A.**, Rushton, A. B., Martinez-Valdes, E., Heneghan, N. R., Gallina, A. Falla, D. 2019. The effect of chronic, non-specific low back pain on superficial lumbar muscle activity: a protocol for a systematic review and meta-analysis. *BMJ Open*, 9, e029850. **(Appendix 3)**

2 – Abstract

Chapter one examined what is commonly known regarding muscle activity in people with CNSLBP, however the changes in muscle activity previously reported have been conflicting with no clear conclusion for how muscle activity is altered in people with CNSLBP. This Chapter reports in full a systematic review which investigated how the magnitude of muscle activity is altered in individuals with CNSLBP. This review followed a published protocol (PROSPERO - CRD42019125156) and is reported in line with the PRISMA and PRISMA-P statements. The Web of Science, PubMed, MEDLINE, EMBASE, ZETOC and CINAHL databases were searched, along with grey literature. Two reviewers independently assessed eligibility of studies, and the risk of bias within eligible studies using a modified Newcastle Ottawa Scale. The cumulative quality of evidence was assessed using GRADE. A total of 3367 non-duplicate records were identified and, following screening, 23 studies were included. A narrative approach to analysis was taken due to the heterogeneity within the methodology of included studies. The cumulative quality of evidence in this review was very low, but a majority of studies identified no differences in muscle activity in people with CNSLBP, compared to pain free controls. This result was largely consistent when results were sub-grouped by muscle (paraspinal/*multifidus*/ES), and type of contraction (static/isometric/dynamic/isotonic). It was suggested that further research with more methodologically rigorous studies were required to address this question, and increase the quality of evidence. Specifically, studies which investigated muscle activity using HDEMG in the ES during static and dynamic flexion and extension tasks may be likely to identify novel results.

2.1 - Introduction

2.1.1 – Rationale

As discussed in the introduction to this thesis, CNSLBP is a leading cause of disability, placing a high burden on healthcare services globally (Hoy et al., 2014, Hong et al., 2013). Therefore, efforts in healthcare research have included a focus on understanding the mechanisms underlying the maintenance of pain in CNSLBP.

One potential physical contributing factor to CNSLBP is variation in the level of activity of the lumbar paraspinal extensor muscles. This has the potential to change the way in which spinal structures are used in movement, and thus contribute to the maintenance and/or perpetuation of pain (Falla and Hodges, 2017). However, despite several investigations, a clear relationship between the level of muscle activity and the perpetuation of CNSLBP symptoms remains unclear (Geisser et al., 2005, Marshall and Murphy, 2008, Russo et al., 2018, Falla and Hodges, 2017). The lumbar region is highly muscular, comprising subcutaneous contributions from the lumbar ES (*iliocostalis, longissimus* and *spinalis*) and the superficial fibres of the *multifidus* (Bogduk, 2005). These muscles are considered particularly important due to their role in nearly all functional spinal movements and postural control tasks (Christophy et al., 2012, Daggfeldt and Thorstensson, 2003). The most common technique used to investigate lumbar muscle activity is EMG (Abboud et al., 2014, Falla et al., 2014, Tucker et al., 2009).

Two previous systematic reviews have attempted to synthesise muscle activity results in people with CNSLBP to draw conclusions; however, these reviews have focussed on the activity during one task (*e.g.* standing on unstable surfaces) (Ehsani et al., 2017), or synthesising results drawn from one database (Geisser et al., 2005). These two systematic reviews were critically assessed using the AMSTAR-2 checklist to appraise the quality of existing reviews in

the field (Shea et al., 2017). Ehsani et al. (2017) used a systematic search strategy across eight databases to assess paraspinal surface EMG in any study which used standing on an unstable surface for a perturbation in individuals with CNSLBP. Within this review, the authors highlighted the inconsistent methodologies used but identified an increase in the voluntary muscle activity of the superficial paraspinal muscles during this task (Ehsani et al., 2017). However, within this review, three flaws in AMSTAR-2 critical domains (CD) were identified (No previously stated methods, incomplete justification of excluded studies, no publication bias assessment) which resulted in a low confidence rating of the review quality (Shea et al., 2017). In the most recent review of multiple tasks, studies which reported muscle activity across all paraspinal muscles were identified from searches on just one database. In this review, it was noted people with CNSLBP showed increased muscle activity during static standing, and lower flexion-extension relaxation ratios, however other outcomes were less clear (Geisser et al., 2005). In this review, flaws in four CDs were identified using the AMSTAR-2 methodology (No previously stated methods, inadequate literature search, incomplete justification of excluded studies, no publication bias assessment) which resulted in a low confidence rating of the review quality (Shea et al., 2017). While these reviews do answer specific questions within their defined objectives, due to the narrow focusses there remains a gap in the literature to assess the overall relationship between CNSLBP and lumbar paraspinal muscle activity.

No previous review has utilised a rigorous systematic search strategy to synthesise findings across tasks and to understand the general effect of CNSLBP on lumbar muscle activity. Understanding the differences in muscle activity between people with CNSLBP and healthy or asymptomatic controls is relevant since understanding the how the muscle activity in the paraspinal muscles is altered in CNSLBP may lead to the development novel approaches to support rehabilitation (Jiang et al., 2010).

2.1.2 – Objectives

The primary objective is to explore what differences are present in the magnitude of activity of the superficial lumbar paraspinal musculature during functional back-specific tasks in people with CNSLBP compared to healthy controls.

The secondary objectives for this review include exploring how these results are altered when results for individual muscles, and contraction types are evaluated individually during functional back-specific tasks in people with CNSLBP compared to healthy controls. If possible, to quantify the magnitude of changes in muscle activity associated with CNSLBP with regard to the intensity/duration of CNSLBP symptoms.

2.2 – Methods and Analysis

The protocol for this systematic review was developed in accordance with the Cochrane Back Review Group guidelines, the Cochrane Handbook, and the PRISMA-P preferred reporting guidelines (Furlan et al., 2009, Green and Higgins, 2011, Moher et al., 2015, Shamseer et al., 2015). The protocol was registered on PROSPERO (CRD42019125156) on the 12/02/2019, and published (Sanderson et al., 2019c). The systematic review is reported in line with the PRISMA statement (Appendix 4) (Liberati et al., 2009, Moher et al., 2009).

Three minor amendments were made from the published protocol in order to adjust to the issues which were unanticipated from the screening searches. (1) As discussed in section 1.1.1, persistent LBP is a complex and ill-defined sub-group of CNSLBP. Thus, in order to focus this review, it was decided to exclude participants who had explicitly not experienced three months of CNSLBP in the previous 12 months. (2) To focus the results and findings of the review more closely on the lumbar region, non-back-specific tasks were excluded. Only tasks which required the voluntary activation of the lumbar paraspinal muscles above all other muscle groups in order to produce the movement were included. (3) The definition of a 'case-study' was ill-defined, as such a large number of case-series were included in the amassed literature. In order to ensure that the results of the review were not swayed by extremely small sample sizes, studies with five or fewer participants were excluded as case-studies or case-series as these were not expected to have adequate power (Turner et al., 2013).

2.2.1 – Eligibility Criteria

The PICOS framework was used in an adapted form to inform the eligibility criteria for the inclusion and exclusion of studies (Smith et al., 2011, Shamseer et al., 2015). The PICOS tool is thought to be the optimal search tool in reviews with limited resources, as is the case here, compared to the slightly more comprehensive PICO tool and observationally focussed SPIDER tool (Methley et al., 2014). The PICO tool has been shown to have higher sensitivity but less specificity compared to the PICOS tool, however this means that a larger number of potentially irrelevant studies may be identified using the PICO method. Compared to the SPIDER tool, the PICOS technique has been demonstrated to have equal or higher sensitivity and equal or lower specificity (Methley et al., 2014). As such, it was determined that the PICOS tool offered the optimal combination of sensitivity and specificity compared to the other tools, in order to complete a detailed and thorough search. The inclusion and exclusion criteria for this review are summarised in Table 2.1.

Population

The population of interest was adults (aged 18-65 years) with CNSLBP as defined in Chapter 1, section 1.1.1, and adults who are pain-free and included in the context of a comparative control.

Intervention/Exposure

The exposure of interest is the use of surface EMG to measure the level of activity of the lumbar musculature. This includes any measure of activity in any lumbar paraspinal muscle

which has been measured by surface EMG, including, but not limited to, the lumbar ES or any of its component parts and the lumbar *multifidus* (Barbero et al., 2012, Geisser et al., 2005, Heydari et al., 2010).

Comparison

Studies including a comparison of muscle activity related to a back-specific functional task were included. This comparison could be within- or between-groups and could include pre- and post-task measures; continuous or multiple measurements throughout a task; or associated with a change in symptoms (Tassinary et al., 2007).

Outcomes

The outcome of interest was the measurement of the amplitude of lumbar paraspinal muscle activity. Any measure related to the amplitude of muscle activity was included, including RMS, average rectified value (ARV) and area under the curve [integrated EMG; (iEMG)] in both absolute values (voltage) and relative to reference contractions including maximal, submaximal or reference voluntary contractions (MVC, SMVC, RVC respectively) (van Dieen et al., 2003). Only studies which measured the level of activity of the muscle quantitatively were included.

Studies

From scoping searches, it was determined that the highest level of evidence for this review was likely to comprise of observational studies (*e.g.* cross-sectional).

Inclusion Criteria	
Population	Adults (18-65y), Male and Female with CNSLBP or a pain-free control
Intervention/Exposure	Use of surface EMG to measure the amplitude of activity of the lumbar paraspinal musculature
Comparison	Differences in the magnitude of lumbar muscle activity between people with CNSLBP and pain-free controls
Outcomes	Surface EMG measurement of the amplitude of muscle activity
Study Type	Quantitative Observational Studies
Exclusion Criteria	
Population	Studies with five or fewer participants in each group People with CNSLBP defined by study authors as 'Chronic' but symptoms had not persisted for over three months or had explicitly not been present for at least three months in the previous year People with CNSLBP who were diagnosed with an underlying pathology or who had received surgery
Intervention/Exposure	Results from the use of intramuscular EMG in tandem with surface EMG Tasks which involved measurements over repeated sessions or included treatment, interventions or training
Study Type	Results from single case studies and case series
Additional Criteria	To reduce the risk of the introduction of bias, studies of all languages were included in the search, however due to limitations in time and resources, studies not in English were excluded

Table 2.1 – Summary of inclusion and exclusion criteria

2.2.2 – Information Sources

Information sources were searched from inception to 21/08/2019. Specific search strategies utilising medical subject heading (MESH) terms were developed to use where appropriate. The following databases were used for searching; Web of Science, PubMed,

MEDLINE (OVID Interface), EMBASE (OVID interface), ZETOC and CINAHL (EBSCO interface).

Hand searching of key journals included the Journal of Electromyography and Kinesiology, Clinical Neurophysiology, Muscle & Nerve, Clinical Biomechanics and the Clinical Journal of Pain. Notable authors in the field were contacted to identify further relevant literature. Grey literature was included, and searches were conducted using the British National Bibliography for report literature, Opengrey and dissertation abstracts. Selected conference proceedings from 2017-2019 were accessed, including the Congress of the International Society of Electrophysiology and Kinesiology, the World Congress of Biomechanics, Society for Back Pain Research Annual Meeting and the World Congress on Low Back & Pelvic Girdle Pain. The reference lists of studies identified as eligible following the search were hand searched to ensure that no relevant studies were missed.

2.2.3 – Search Strategy

The search was conducted by the lead author (AS) and the design of the search was informed by the PICOS criteria outlined previously, subject specific expertise and the completion of scoping searches. There were no restrictions on the search in terms of the design, language, region, or date. The keyword search strategy was developed for MEDLINE (OVID interface) and included MESH keywords to ensure completeness of the search. The specific search terms were modified to reflect differences in keywords and syntax between databases (Lefebvre et al., 2019), however the search strategy remained consistent; an example of the search strategy for the Medline database is included in Appendix 5. All information sources were searched to identify relevant studies, and subsequently all duplicates removed.

2.2.4 – Data Management

The results of the literature search, including the citation and abstract for each relevant study was imported into EndNote X9 (Clarivate Analytics). Studies were imported during the search, and duplicate studies removed prior to the screening process. In order to screen effectively, the full text for all potentially eligible studies was retrieved and stored in EndNote X9. Screening was accomplished using forms which were developed and piloted to reflect the previously stated inclusion and exclusion criteria.

2.2.5 – Selection Process

The study selection process was designed to reflect the best practice guidelines suggested by the Cochrane Back Review Group (Furlan et al., 2009). Two reviewers (AS, AG) independently screened the identified studies. The reviewers were not blinded to the authorship, research group, or institutional information of the studies. Initial screening of search results excluded studies in which it was clear from the title and abstract that the content was not relevant to objectives of this review. Where eligibility was unclear, the reviewers read the full text of the article and used the screening tool to assess inclusion. The screening form was used to objectively assess the study based on the inclusion and exclusion criteria. This form identified studies as eligible, ineligible or unclear in terms of its inclusion in the review. In the event that a study was identified as unclear it was discussed with the second reviewer to determine eligibility. If there was no consensus following this, discussion with a third reviewer (DF) took place to determine the eligibility of the study. Furthermore, in the instance that one reviewer was an author on a potentially eligible study, screening for inclusion was conducted by the remaining and third reviewer in order to reduce the risk of bias.

2.2.6 – Data Collection Process

Data were extracted using a standardised form, based on the Cochrane data extraction template, using the objectives of the review and the inclusion criteria as a guide (Green and Higgins, 2011). The extracted data were reviewed for accuracy by the second reviewer and any discrepancies discussed between reviewers. Where resolution could be achieved, discussion with the third reviewer determined which data were relevant. The standardised proforma was piloted for completeness of data extraction on an initial subsection of studies and necessary changes were made prior to extraction from all eligible studies.

2.2.7 – Data Items

A summary of data items extracted from eligible studies is included in Table 2.2. Where data were missing from studies or the results were unclear, the corresponding author was contacted for clarification. Lead and/or corresponding authors were contacted by email, and reminder emails were sent one week later. If the clarification affected the eligibility of the study, and the author did not respond within one week of the stated email deadline (a total of four weeks), the study was considered ineligible. If a study was believed to have used the same sample as another eligible study, the authors were contacted prior to inclusion for clarification to ensure that the results were not recorded in duplicate.

Information Area	Data Extracted
Background	Authors Year of Publication Title
Methodology	Sample Characteristics (Sample size, age, anthropomorphic data) CNSLBP Characteristics (Duration, average pain, current pain, laterality) Task Information (Fatiguing, endurance, repeated, standing, length of recording, etc) Type of surface EMG (bipolar, linear array, HDEMG) EMG Processing (sampling frequency, filtering, offline processing) EMG Processing of signal amplitude (RMS, ARV, integrated EMG) Muscles measured Absolute or Normalised Activity values Normalisation Parameter and technique (MVC, SMVC, RVC)
Results	Amplitude Outcomes (Within subjects Pre/Post, between subjects pre/post, changes throughout, systematic differences between groups) Effect Sizes where reported

Table 2.2 – Summary of items extracted from eligible studies using the standardised data extraction form

2.2.8 – Risk of Bias

Risk of bias of individual studies was assessed independently by each reviewer (AS, AG) using a modified version of the Newcastle-Ottawa scale (NOS) (Wells, Accessed 2018). The published scales were designed and validated for use within longitudinal case-control and cohort observational studies and considers the selection and comparability of the sample as well as the assessment of the outcomes over time (Hootman et al., 2011). Previous investigations into the reliability and the validity of NOS have presented mixed results, showing in some cases lower reliability when compared to other tools (Hootman et al., 2011, Hartling et al., 2013). However, more than 86 individual risk of bias tools have been created for observational studies, with a systematic review of tools indicating that there was no clear preferable candidate for

determining risk of bias (Sanderson et al., 2007). For this review, it was decided to follow the advice of Hootman and colleagues, who determined that the NOS remains preferable to alternate risk of bias tools despite its poor-moderate reliability (ICC = 0.52; 95% CI = 0.14, 0.76) and unclear validity beyond face validity, due to the ease of use across observational designs (Hootman et al., 2011).

Where eligible studies were cross-sectional in design, with just one experimental session, a modified version was required. The justifications for the changes made are tabulated in Table 2.3 and the cross-sectional NOS scale modified for this review and supplementary details of changes are included in Appendix 6. Adaptations were made only where necessary from the case-control version of the tool, and where possible, changes were avoided or very minor, to ensure that the tool was used appropriately. The process for these changes included an individual assessment of each question in the existing case-control NOS in line with the scoring manual to understand how biases were being evaluated (Wells, Accessed 2018). Where changes were required, these were preferentially limited to be in line with the scoring manual where possible to maintain the validity of the tool. In instances where larger changes were needed (Q7 and Q9), there was no clear precursor as prior adaptations of this tool reflected review specific outcomes (Epstein et al., 2018, Modesti et al., 2016). As such, these changes were made following discussions between reviewers and reflected clear bias outcomes as defined in the manual. Nonetheless, while every effort was made to ensure that the tool remained close to the validated format, it should be noted that the major changes to these questions may affect the validity of results for the 'Outcome' section, and should be interpreted accordingly (Guyatt et al., 2011e, Boutron et al., 2019).

As in the published version of the tool, each study was designated a star rating from 0 to a maximum of nine stars, for which guidelines exist to convert to Agency for Healthcare

Research and Quality Standards (Borge et al., 2017, Uribe-Restrepo et al., 2018). Using these guidelines, included studies were graded as 'Good', 'Fair' or 'Poor' quality, with poor quality indicating studies at risk of bias. Where reviewers were required to assess the risk of bias of papers for which they are an author, this would be completed by both reviewers, however if there was disagreement then scoring would be discussed with the third reviewer.

Question Number	Changes	Justification
Section 1	**Minor question wording changes**	
1	No Changes made	This question seeks to identify how the LBP/Con groups have been verified in terms of their symptoms or lack thereof.
2	Addition of a second category	An additional category has been added to account for the sample meeting the eligibility criteria and participating, but not being fully representative of the clinical population with consistent high-levels of pain and disability. Therefore, this ensures that the individuals meet the inclusion criteria and so show no sampling bias.
3	Modification of second category	The original wording relied on cases being recruited from a hospital or structured recruitment process. The question sought to identify if the only differences between cases and controls was the presence of the case symptoms and both arose from the same community. The new wording allows for the high possibility of cases not being recruited from a hospital setting, which would remove the possibility of hospital controls. Instead the category allows for the classification of if the cases and controls were recruited from the same population or if a different sampling method was used for controls which could introduce selection bias.
4	Rewording of second category	This question is assessing if bias could be introduced through the inclusion of individuals who have previously had the case symptoms, if that should be an exclusion criterion. The new wording is copied from the original manual for coding this question in the NOS for case-control studies, therefore ensuring that the essence of the question is maintained.
Section 2	**Minor Alterations**	
5	A third category has been included and specific factors have been included.	Population demographics (higher, weight, age, BMI) have been selected as the factor to control for, as the primary outcome could be affected by anthropomorphic features. The coding manual suggests that if these criteria are not met or if groups are comparable by coincidence after the fact, then no stars should be allotted for this section. In this modification

		this additional category has been added to ensure that this question is answered and no stars are intentionally given, rather than the question accidentally left blank through error.
Section 3	**Major Changes**	**Questions in this section have required the most modifications as the original section sought to ascertain if the cases and controls were exposed to the variable of interest. In studies included here, the variable of interest is the EMG activity and by participating in the experiment, it is known that cases and controls are exposed.**
6	This question has been specifically re-written for the EMG exposure.	The original question assessed the possibility of bias being introduced through the accidental inclusion of individuals as cases who have not been exposed to the variable of interest. In this review, there are two exposures, one to LBP and one to the EMG and task. Exposure to non-specific LBP is not externally verifiable as it is an 'invisible disability' so all included studies would be ranked as 'self-report'. The interpreted essence of this question regards how it could be proven that the results arise from the exposure of the individual to the variable. Therefore, here this question has been used to assess how the EMG principles are applied to ensure that it is applied consistently across groups and that the EMG activity results do not arise from a variable placement of electrodes.
7	Slight change in the question wording	This question asked if the answer to Q6 was the same for both cases and controls. As Q6 has been modified, the title of this question has been slightly modified to reflect this change.
8	This question has been specifically re-written for the task completed	The original question assessed if reporting bias has been introduced through different numbers of participants in each group not responding to follow-up/the variable of interest. The new structure instead assesses if the task, which is the element of the study which occurs across time, has been implemented in the same way for all participants. This question now therefore assesses if bias may have been introduced through non-standardised task instructions.

Table 2.3 – Tabulated outline of the modifications made to the NOS from the case-control version (Wells, Accessed 2018) for use in cross-sectional studies.

2.2.9 – Data Synthesis

In order to be included in meta-analysis, the outcomes and the methodology of included studies must be homogenous, which was not the case in this review. Studies were determined to be heterogeneous based on the following characteristics;

- Type of sEMG used (*e.g.* Bipolar or HDEMG)
- Measurement of muscle activity outcome (e.g. relative or absolute measurement)
- Target muscles (*e.g.* ES, *multifidus*)
- Task completed (e.g. fatiguing, endurance, repeated)

As such, a narrative synthesis was used, with more binary elements of analysis included where possible (*e.g.* number of studies with similar conclusions) (McKenzie and Brennan, 2019). Results were structured for analysis by the task completed by participants, and in further analyses grouped by muscle investigated, and by the type of contraction performed (*e.g.* dynamic/isotonic). As no meta-analyses could be performed a narrative vote counting approach was used to synthesise these results, whereby studies were classified by the most supported outcome; the primary result most supported by the individual results of outcomes within a study. In this approach, if a study measured 12 outcomes related to trunk flexion and nine supported outcome A and three supported outcome B, the majority supported outcome for this study would be for outcome A (McKenzie and Brennan, 2019). Individual comparisons between groups within studies were aggregated and the results of the study distilled into the format of an ‘increase’, ‘decrease’ or ‘no change’ in activity in the muscle activity for each task (McKenzie and Brennan, 2019). Where no clear outcome was supported, (*e,g.* an equal number of outcomes reported increases and no changes in activity), in order to avoid an over-

simplification of the results, the study was classified as having mixed/unclear results and the two component outcomes were stated (McKenzie and Brennan, 2019). This process was repeated for the additional objectives, with groupings made by the muscle investigated, and separately by the type of contraction required for the task. Within these subgroupings the same process was repeated as above to categorise the results.

2.2.10 – Confidence in Cumulative Evidence

The pooled data were assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach to evaluate the overall quality of the literature (Goldet and Howick, 2013). The GRADE approach was applied to the subgroupings identified earlier (*e.g.* muscle), and in accordance to the published guidelines (Guyatt et al., 2008). Thus, observational studies were initially be given a 'Low' rating for the quality of evidence, and then up- or downgraded from this point (Balshem et al., 2011). Studies were upgraded for factors such as large effect sizes or dose-response relationships between CNSLBP severity and activity; or downgraded for factors including risk of bias, publication bias, imprecision, inconsistencies between studies, and indirect relationships with results (Guyatt et al., 2011a, Guyatt et al., 2011b, Guyatt et al., 2011c, Guyatt et al., 2011d, Guyatt et al., 2011e, Balshem et al., 2011). The risk of publication bias was assessed through the grey literature identified within the searches. Additionally, where conference proceedings were identified within the search, authors of presented studies were contacted to assess if the material had been brought forward to publication. Imprecision and inconsistencies between studies were defined according to the GRADE criteria, which recommends the use of CI's to confer precision and consistency (Guyatt et al., 2011a).

Following this process, a final judgement for overall level of evidence level was made (*e.g.* 'High', 'Moderate', 'Low' or 'Very Low') which can be interpreted in line with the GRADE guidance to give a recommendation for the interpretation of the evidence as 'strong' or 'weak' (Balshem et al., 2011, Furlan et al., 2009, Goldet and Howick, 2013, Guyatt et al., 2008).

2.2.11 – Patient and Public Involvement

To ensure that this review was conducted in a way which is useful to the patients whom it is intended to benefit, the topic of this review was discussed at established patient and public involvement meetings and the focus of the review was refined based on feedback. To achieve this, the rationale and aims underlying this review were outlined to panel members and feedback was collected on the perceived utility and suggestions for expansion. Beyond this, members of the panel were not involved in the analysis and data collection of the systematic review.

2.4 – Results

2.4.1 – Study Selection

Following the searches, 6936 articles were identified for potential inclusion within this review. After removal of duplicates there were 3367 articles, which were screened by title and abstract. Full-text screening was completed for 147 articles. Following independent assessment by the two reviewers, three studies went to the third reviewer over unclear age and CNSLBP criteria, two were included and one excluded at this stage. Thus, a total of 24 publications arising from 23 studies were included (Fig. 2.1, Table 2.4). Across the included publications, two publications resulted from the same study and thus shared a sample (Ng et al., 2002b, Ng et al., 2002a), thus results have been combined and will be collectively referred under one study reference (Ng et al., 2002a). Seven studies were excluded from this review as authors did not respond to contact and so eligibility, primarily on CNSLBP characteristics criterion, could not be determined (Chiou et al., 1999, Finneran et al., 2003, Grabiner et al., 1992, Kim et al., 2013, Kumar and Prasad, 2010, Kuriyama and Ito, 2005, Linsinski, 2000). The results from a study detailed later within this thesis (Sanderson et al., 2019b) were excluded from the review at this stage, as its design was influenced by the results of the initial iteration of this review designed to inform this thesis.

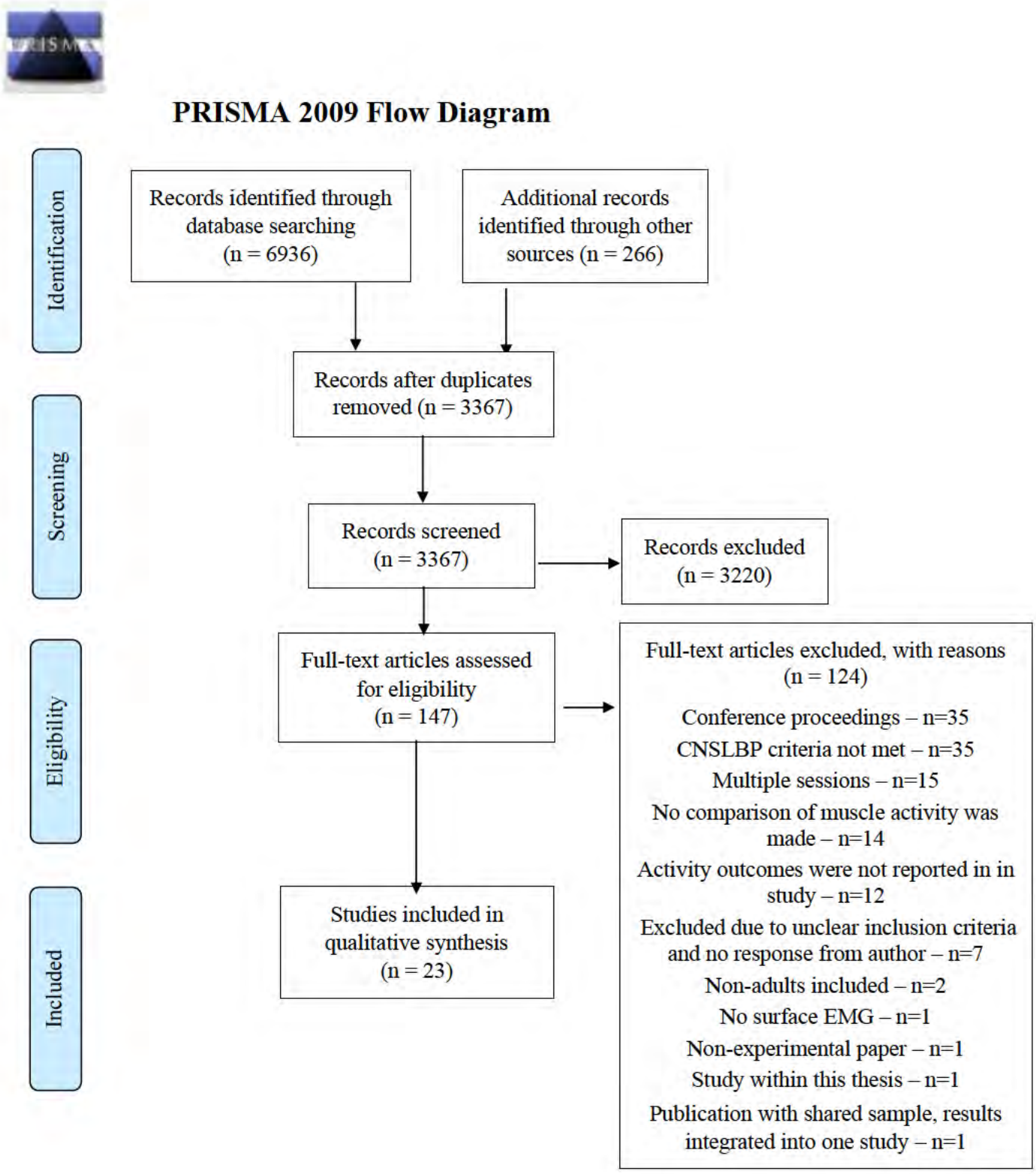


Fig. 2.1 – Prisma flow diagram for the searching and screening procedure, adapted from Moher et al. (2009)

Study	CNSLBP Participants				Control Participants			Contraction Type	Task Characteristics	
	n	Sex	Age (years)	CNSLBP Duration	n	Sex	Age		Task Category	Task Synopsis
Adams, 2006	23	-	20-55	> 6 months	23	-	20-55	Dynamic	Trunk Extension	From standing, enter hyperextension and return
									Axial Rotation	From standing, with fixed pelvis rotate to one side
									Trunk Flexion	From standing, flex fully and return to standing
Ambroz et al., 2000	20	-	-	> 6 months	30	22m/ 8f	41 ±7.3	Static	Flexion	Maximal trunk flexion
								Dynamic	Flexion and Extension	From standing, flex fully and return to standing
Cimbiz et al., 2006	32	16m /16f	21.45 ±1.79	> 3 months	28	14m/ 14f	21.45 ±1.19	Static and Dynamic	Lateral Flexion	From standing, full lateral flexion to one side
									Trunk Flexion	From standing, flex fully and pause at end range
									Trunk Extension	From standing, enter hyperextension pause at end range
									Axial Rotation	From standing, rotation of the trunk to one side, pause at end range
									Prone Trunk Extension	Lifting sternum from plinth with arms at side
									Prone Trunk Extension	Lifting sternum from plinth with arms in reverse T
									Prone Trunk Extension	Lifting sternum from plinth with arms stretched overhead
Cohen et al., 1986	13	9m/ 4f	46	> 6 months	13	8m/5 f	42	Static	Trunk Flexion	45° trunk flexion at waist
									Trunk Flexion	Full trunk flexion at waist
									Lumbar Pelvic Tilt	Roll pelvis forward by increasing the lumbar curve
Collins et al., 1982	11	9m/ 2f	45	> 6 months	11	7m/4 f	42.5	Static	Trunk Flexion	45° trunk flexion at waist
									Trunk Flexion	Full trunk flexion at waist
									Lumbar Pelvic Tilt	Roll pelvis forward by increasing the lumbar curve

Danneels et al., 2002	51	23m /28f	40.82 ±11.8	> 12 months	77	33m/ 44f	36.28 ±10.45	Dynamic	Combined Trunk Tasks	Standing Trunk flexion, weighted trunk flexion, trunk flexion and rotation, seated trunk flexion and rotation
de Aquino Nava et al., 2017	19	19f	46.31 ±8.47	> 3 months	15	15f	39.8 ±8.01	Dynamic	Flexion and Extension	From standing, flex fully and return to standing
									Flexion and Extension	From standing, flex fully and return to standing holding 5% of max load
									Flexion and Extension	From standing, flex fully and return to standing holding 10% of max load
Descarreaux et al., 2007	14	11m /3f	36.6 ±12.8	> 6 months	15	10m/ 5f	34.5 ±12.9	Isometric	Flexion and Extension	Participants alternately flexed and extended the trunk against 70% and 50% MVC
Djordjevic et al., 2015	36	18m /18f	53.22 ±8.12	3< x <6 months	37	15m/ 22f	52.55 ±9.45	Static	Prone Trunk Extension	Lumbar extension with arm held at 120° abduction
Du et al., 2018	88	18m /70f	35.56 ±7.28	3< x <12 months	83	21m/ 62f	34.27 ±5.87	Dynamic	Trunk Flexion	From standing, flex fully and return to standing
									Trunk Extension	From standing, extend fully and return to standing
									Lateral Flexion	From standing, flex laterally to one side fully and return to standing
Ershad et al., 2009	10	10f	25.4 ±4.6	< 3 months	10	10f	24.7 ±4.1	Static	Trunk Flexion	30° flexion from a neutral position
									Trunk Flexion	30° flexion from a neutral position with 6kg weight
									Trunk Flexion	30° flexion from a neutral position with 12kg weight
Falla et al., 2014	19	8m/ 11f	32.2 ±9.5	> 3 months	17	9m/8 f	29.4 ±7.4	Dynamic	Lifting	Repeated sagittal lifting of a 5kg box between two shelves
Kankaanpaa et al., 2005	17	17m	39.9 ±6.6	> 3 months	12	12m	42.1 ±7.7	Dynamic	Seated Trunk Extension	Repeated resisted trunk extensions between 25° flexion and 5° extension
Kankaanpaa et al., 1998	20	20f	45.2 ±4.6	> 3 months	15	15f	42.3 ±7.2	Isometric	Seated Trunk Extension	Resisted lumbar extension at 30° flexed position against 50% MVC
Kienbacher et al., 2017	132	-	38.90 ±12.71	> 3 months	46	-	36.28 ±12.60	Isotonic	Flexion and Extension	From sitting, flex fully and return, pause at 50% of movement against 80% MVC resistance
Lariviere et al., 2002	15	15m	40 ±4	> 3 months	18	18m	39 ±3	Dynamic	Lifting	12kg box lifted from floor to trochanter height and returned to floor

									Combined Trunk Tasks	12kg box lifted from floor to lateral (right) shelf at trochanter level and returned to floor
Lima at al., 2018	40	33m /7f	35.2 ±9.3	> 3 months	40	29m/ 11f	35.9 ±7.7	Dynamic	Lifting	1kg medicine ball was picked off the floor, held and returned to the ground
Lin et al., 2001	47	26m /21f	39.5	> 6 months	45	25m/ 20f	28.1	Static	Trunk Flexion	Lower limbs restrained, maximal flexion at waist
									Trunk Extension	Lower limbs restrained, maximal extension at waist
Ng et al., 2002a	12	12m	28.3 ±6.7	> 12 months	12	12m	30.0 ±7.6	Isometric	Axial Rotation	In restrained standing, constant resisted axial rotation at 80% MVC
									Axial Rotation	In restrained standing, resisted axial rotation at 30%, 50% and 70% MVC
Pirouzi et al., 2006	30	30f	27.3 ±8.1	> 6 months	30	30f	27.5 ±7.9	Isometric	Axial Rotation	In restrained standing with arms across the chest without pelvic support; 25% MVC
									Axial Rotation	In restrained standing with arms across the chest with pelvic support; 25% MVC
									Axial Rotation	In restrained standing pushing up with arms without pelvic support; 25% MVC
									Axial Rotation	In restrained standing pushing up with arms with pelvic support; 25% MVC
Rossi et al., 2017	14	14f	24.14 ±3.13	> 6 months	14	14f	22.21 ±3.4	Isometric	Seated Trunk Flexion	At 60° flexion, alternate maximal flexion against resistance
									Seated Trunk Extension	At 60° flexion, maximal extension movement against resistance
Shirado et al., 1995	20	12m /8f	34.1	> 6 months	25	13m/ 12f	23.8	Static and Dynamic	Flexion and Extension	From standing flex fully, pause, and return to standing
Yang, 2018	28	-	22.67 ±1.38	> 6 months	28	-	23.75 ±3.51	Static	Trunk Flexion	Stoop lifting, 30° static flexion holding bodyweight
									Trunk Flexion	Stoop lifting, 30° static flexion holding bodyweight + 10% bodyweight
									Trunk Flexion	Stoop lifting, 30° static flexion holding bodyweight + 20% bodyweight

Table 2.4 – Breakdown of studies included within this review and the associated sample and task information and synopsis

2.4.2 – Study Characteristics

2.4.2.1 - Population

Sample sizes ranged between 10-132 participants per group, with a mean (+/-SD) sample size of 30.2±27.2 for the CNSLBP and 27±19.1 for the control groups. Within the reviewed studies, participants ranged in age from 18-65; with a mean age among studies of approximately 35.65 years for the LBP and 33.77 for the control participants, however this has not been weighted by sample size which precludes standard deviation estimations. Two studies did not include a mean age for all participants (Adams, 2006, Ambroz et al., 2000), and one study included individuals over the age of 65, but all results from participants in the 60-90 age grouping were excluded (Kienbacher et al., 2017).

2.4.2.2 - Task and Contraction Type

Collectively, 42 individual tasks were included with trunk flexion the most commonly investigated (n=10). Other tasks comprised of trunk extension (n=4), combined flexion and extension (n=4), seated trunk extension (n=3), seated trunk flexion (n=2), prone trunk extension (n=2), lifting (n=3), trunk rotation to the left (n=4) and right (n=4), lateral trunk flexion (n=2), lumbar pelvic tilt (n=2), and a combination of trunk focussed tasks (n=2) (Table 2.4). Across included studies, the tasks completed were static/isometric in nature (n=11), dynamic/isotonic (n=9) or a combination of both (n=3).

Within studies multiple outcomes were assessed, a total of 147 comparisons of muscle activity were made between groups and static/isometric tasks accounted for 74 comparisons of muscle activity in total. Within subgroup of static/isometric contractions, all comparisons for

trunk flexion, lumbar pelvic tilt, and prone trunk extension were conducted in static positions and the remainder of these comparisons were isometric contractions against resistance. Dynamic/isotonic contractions comprised the remaining 73 comparisons, with two comparisons investigating isotonic contractions in one study and 71 comparisons made from dynamic contractions.

2.4.2.3 – Electromyography

Of the 23 studies included within this review, 22 used bipolar EMG and the remaining study used HDEMG (Falla et al., 2014). Within and between studies, the ES was the most investigated muscle with 13 studies recording activity from this muscle in 15 locations; some studies investigated more than one site. The *multifidus* was recorded in 11 instances across 11 studies, and non-specific lumbar paraspinal muscles were recorded in nine sites across six studies. The placement of electrodes over the ES showed the greatest variation, with landmarks from L1 to L5 used for positioning. The placement of electrodes to record muscle activity over the multifidus was the most consistent, with several studies reporting use of guidelines for electrode placement (Table 2.5).

Within the studies included in this review, nine studies used absolute values for amplitude and the remaining 16 studies reported normalised results. Where performed, the normalisation process exhibited further inconsistency with initial values, reference values, submaximal and maximal voluntary contractions all used as reference points. Following processing, while all studies included in this review presented muscle activity outcomes, eight published no numerical results to support stated results (Adams, 2006, Cohen et al., 1986, Du et al., 2018, Ershad et al., 2009, Falla et al., 2014, Kankaanpaa et al., 1998, Kienbacher et al., 2017, Ng et

al., 2002a, Pirouzi et al., 2006), and four further studies did not include numerical results for all activity-specific outcomes (Ambroz et al., 2000, Collins et al., 1982, Shirado et al., 1995, Yang, 2018). Within the studies where numerical results were included, one study reported only percentage changes from baseline (Shirado et al., 1995), one presented the difference between groups (Lima et al., 2018) and one presented median results, in contrast to more commonly reported mean results (Danneels et al., 2002).

2.4.2.4 – CNSLBP Characteristics

The duration and severity of CNSLBP symptoms were poorly reported among studies, with most studies reporting minimum criteria for symptom duration and no further information or outcomes following testing. Average pain ranges were reported in five studies (Adams, 2006, Djordjevic et al., 2015, Falla et al., 2014, Kienbacher et al., 2017, Lima et al., 2018), current pain levels on the day of testing in seven studies (Cimbiz, 2006, Descarreaux et al., 2007, Du et al., 2018, Kankaanpaa et al., 1998, Ng et al., 2002b, Ng et al., 2002a, Shirado et al., 1995, Yang, 2018), and both average and current pain levels were reported in three studies (de Aquino Nava et al., 2017, Kankaanpaa et al., 2005, Pirouzi et al., 2006). However, even in instances where these outcomes were reported, the methods were not consistent.

A descriptive analysis of the pain characteristics (n participants reported) indicates that the participants with CNSLBP represent a sample (n=316) with 'mild-moderate' average levels of pain, ranging from 2.58-6.93/10 (Breivik et al., 2008). On the day of testing, where reported, pain levels within studies held a slightly lower range from 0.88-5.1/10, also representing very "mild-moderate" pain (n=280). However, further analysis for pain as an outcome of interest was not possible.

Study	Muscle Name	Placement Side	Spinal Landmark	Distance from Landmark
Adams, 2006	Paraspinal	Bilateral	L3	-
Ambroz et al., 2000	Paraspinal	Bilateral	L1-L2	3cm
	Paraspinal	Bilateral	L3-L5	3cm
Cimbiz et al., 2006	Erector Spinae	Bilateral	L2	-
	Erector Spinae	Bilateral	L4	-
Cohen et al., 1986	Paraspinal	Bilateral	L2-L4	2cm
Collins et al., 1982	Paraspinal	Bilateral	L3	2cm
	Paraspinal	Bilateral	L5	2cm
Danneels et al., 2002	Erector Spinae (IL)	Bilateral	L1	Midway to lateral
	Multifidus	Bilateral	PSIS	Just lateral (1 finger)
de Aquino Nava et al., 2017	Erector Spinae (IL)	Unilateral (dominant)	L2-L3	6cm
	Multifidus	Unilateral (dominant)	L5	Line from PSIS to L1/2 – 3cm*
Descarreaux et al., 2007	Erector Spinae	Unilateral (right)	L2-L3	-
	Multifidus	Unilateral (right)	L5-S1	-
Djordjevic et al., 2015	*Multifidus*	Bilateral	L5	Line from PSIS to L1/2 – 3cm*
Du et al., 2018	*Multifidus*	Bilateral		-
Ershad et al., 2009	Erector Spinae	Unilateral (right)	L3	3cm lateral of midline
	Multifidus	Unilateral (right)	L5	2cm lateral of midline
Falla et al., 2014	Erector Spinae	Unilateral (pain/right)	L5-L2/3	2cm
Kankaanpaa et al., 2005	Paraspinal Muscles	Bilateral	L4-L5	2cm
Kankaanpaa et al., 1998	Paraspinal Muscles	Bilateral	L3-L4	2cm
	Paraspinal Muscles	Bilateral	L5-S1	2cm
Kienbacher et al., 2017	*Multifidus*	Bilateral	L5	Line from PSIS to L1/2 – 3cm*
Lariviere et al., 2002	Erector Spinae	Bilateral	L3	3cm
Lima at al., 2018	*Multifidus*	Bilateral	L5	Line from PSIS to L1/2 – 3cm*
	Erector Spinae (IL)	Bilateral	L2	Just lateral (1 finger)
	Erector Spinae (L)	Bilateral	L1	3cm
Lin et al., 2001	Erector Spinae	Bilateral	L3/4	3-4cm

Ng et al., 2002a	Erector Spinae (IL)	Bilateral	L2	Parallel to line from PSIS to border of muscle at rib 12
	Multifidus	Bilateral	L5	Line from PSIS to L1/2 – 3cm*
Pirouzi et al., 2006	Erector Spinae	Bilateral	L3	2cm *
Rossi et al., 2017	Erector Spinae	Bilateral	L1	Just lateral (2 fingers)
	Multifidus	Bilateral	L5	Line from PSIS to L1/2 – 3cm*
Shirado et al., 1995	Erector Spinae	Bilateral	L3	5cm
Yang, 2018	Multifidus	Unilateral (right)	L5	2cm

Table 2.5 – Summary of the muscles considered in the included studies, along with the placement criterion. Where authors made it clear that a standardised system of electrode placement was used, this is denoted by an asterisk. Posterior Superior Iliac Spine (PSIS), 1st -5th lumbar vertebrae (L1-L5), *iliocostalis lumborum* (IL), *longissimus thoracis* (L)

2.4.3 – Risk of Bias within Studies

Most studies were assessed as 'poor' quality category due to a large potential for the introduction of biases. Table 2.6 reports the overall study assessments and the stars awarded by each reviewer in the three domains of the NOS; the selection domain (max four*), the comparability domain (max 2*) and the outcome domain (max 3*). Of the 23 studies included in this review, one study was found to be of good quality due to the low risk of bias identified within the publication. Moderate risk of bias was identified in five studies, which were classified as fair quality; and 17 studies were rated as poor quality due to the high risk of bias identified. (Table 2.6).

The risk of bias scores were primarily affected by reporting of characteristics in the selection and outcome domains. In the selection domain, the case definition of individuals with CNSLBP was universally poor among studies, with almost no independent validation of case status. Additionally, while clear definitions for inclusion in the CNSLBP group were given, the recruitment of the control sample was poorly reported. In the outcome domain, the tasks used were poorly described, which would hinder repetition; and/or were not described to be standardised. Conversely, all studies except for one were described as having the same exposure to the EMG between groups, a factor which reduced bias among studies.

There was a good overall agreement between reviewers of 82.6% on the quality assessment categories for each study during independent assessment (19/23 studies). On individual scores for each question in the NOS, reviewers agreed on the same star rating in 80.4% of outcomes assessed (8 outcomes per study, 148/184 outcomes). Four studies required further discussion between reviewers to determine the combined assessment of the risk of bias, however no studies required mediation from the 3rd reviewer.

Author	Selection Domain		Comparability Domain		Outcome Domain		Independent NOS Assessment		Agreed Combined NOS Assessment
	R1	R2	R1	R2	R1	R2	R1	R2	
Adams, 2006	**	**	**	**	**	**	Fair	Fair	Fair
Ambroz et al., 2000	***	**	**	**	**	**	Fair	Fair	Fair
Cimbiz et al., 2006	-	-	-	-	*	*	Poor	Poor	Poor
Cohen et al., 1986	***	***	**	**	***	**	Good	Good	Good
Collins et al., 1982	***	***	-	-	**	*	Poor	Poor	Poor
Danneels et al., 2002	**	**	-	-	**	*	Poor	Poor	Poor
de Aquino Nava et al., 2017	-	*	**	*	***	***	Poor	Poor	Poor
Descarreaux et al., 2007	**	**	-	-	*	***	Poor	Poor	Poor
Djordjevic et al., 2015	-	*	-	-	**	***	Poor	Poor	Poor
Du et al., 2018	***	***	**	**	**	*	Poor	Poor	Poor
Ershad et al., 2009	-	-	**	-	**	**	Poor	Poor	Poor
Falla et al., 2014	**	**	**	-	**	***	Fair	Fair	Fair
Kankaanpaa et al., 2005	*	*	-	*	***	***	Poor	Poor	Poor
Kankaanpaa et al., 1998	**	**	*	*	***	***	Fair	Fair	Fair
Kienbacher et al., 2017	*	*	**	-	***	**	Poor	Poor	Poor
Lariviere et al., 2002	**	*	-	*	***	***	Poor	Poor	Poor
Lima at al., 2018	***	**	-	-	**	**	Poor	Poor	Poor
Lin et al., 2001	-	-	-	-	**	*	Poor	Poor	Poor
Ng et al., 2002a	*	*	**	**	**	***	Poor	Poor	Poor
Pirouzi et al., 2006	*	-	**	**	***	**	Poor	Poor	Poor
Rossi et al., 2017	**	***	*	*	***	**	Fair	Fair	Fair
Shirado et al., 1995	*	**	-	-	***	*	Poor	Poor	Poor
Yang, 2018	-	-	**	**	**	***	Poor	Poor	Poor

Table 2.6 – Summary table indicating the individual reviewer risk of bias scores in each domain of the NOS and overall risk of bias assessments for each study, and the final agreed risk of bias assessment following discussion between reviewers.

2.4.4 – Results of Individual Studies

Within this section, results are initially considered across all muscles and contraction types and are organised by the task completed, in later sections muscle (section 2.4.8.2) and contraction type (section 2.4.8.3) are used to group the data.

2.4.4.1 – Overall Evidence

Results from 13 tasks were presented across all 23 studies and a total of 42 aggregated outcomes were reported (some studies had reported multiple tasks, resulting in multiple outcomes). Prior to sub-grouping, when assessing the overall evidence for the magnitude of muscle activity in CNSLBP, a majority of studies suggested that there were no differences in this measure across tasks (Fig. 2.2, Table 2.7). Across all contraction types and muscles, there were 29 aggregated task outcomes from studies which supported no differences in muscle activity. Evidence from tasks in six studies showed greater activity in the CNSLBP group and four demonstrated less activity. A further five studies showed mixed results where an equal number of outcomes supported different conclusions (Fig. 2.2).

Trunk flexion demonstrated the greatest variation between reported outcomes, with three studies showing greater muscle activity in LBP, five studies reporting no differences, and one each showing lower activity and mixed results (CNSLBP greater and no difference). Movements in the sagittal plane (flexion/extension; seated and standing) showed some evidence to suggest that there may be lower muscle activity in people with CNSLBP, particularly in standing trunk extension, where two studies apiece provided evidence for lower activity and no differences. There is very little evidence to support any gross differences in muscle activity

during axial rotation in either direction, or lateral trunk flexion with just one study indicating a gross difference between groups in any of these measures.

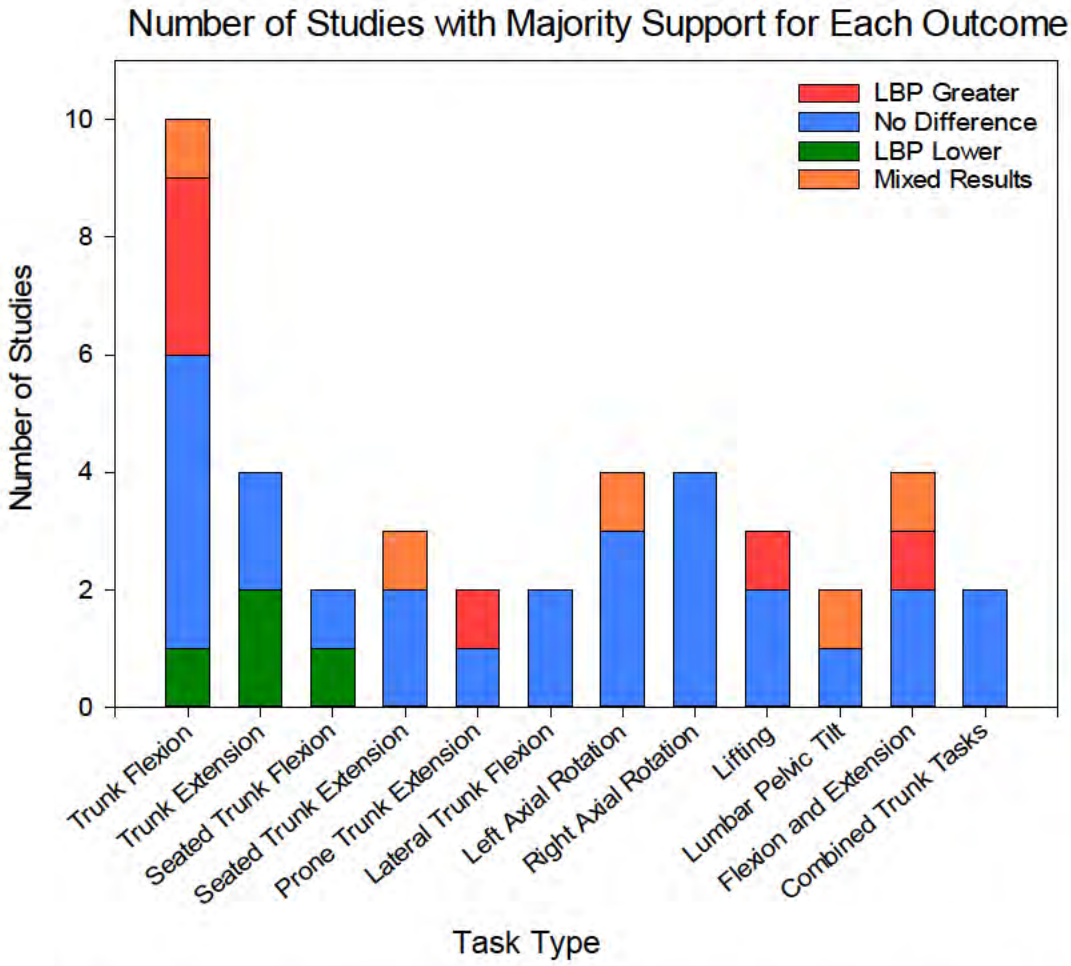


Fig. 2.2 – Outcomes across all individual studies, grouped by the task completed.

The cumulative evidence across all studies was determined to be very low quality according to the GRADE criteria. This rating was made due to the global observational nature of the studies, low precision, publication biases and high risk of bias among studies. Very low quality of evidence from 23 studies indicated that there were no differences in muscle activity.

Task Outline	All Factors Combined					
	Number of Studies (Measures)	Sample Size	Majority Muscle Activity			
			Greater (+)	No Difference (< >)	Lower (-)	Mixed
Trunk Flexion	10 (29)	588	3	5	1	1
Trunk Extension	4 (8)	354	-	2	2	-
Seated Trunk Flexion	2 (5)	88	-	1	1	-
Seated Trunk Extension	3 (10)	93	-	2	-	1
Prone Trunk Extension	2 (4)	133	1	1	-	-
Lateral Trunk Flexion	2 (10)	231	-	2	-	-
Left Axial Rotation	4 (19)	190	-	3	-	1
Right Axial Rotation	4 (19)	190	-	4	-	-
Lifting	3 (22)	146	1	2	-	-
Lumbar Pelvic Tilt	2 (4)	48	-	1	-	1
Flexion and Extension	4 (11)	291	1	2	-	1
Combined Trunk Tasks	2 (6)	161	-	2	-	-
GRADE Assessment	**VERY LOW**					
GRADE Assessment Criteria (score)	High risk of biases (-) Moderate publication biases (-) Inconsistently defined precision (-) Inconsistent results (-) Direct outcomes (+)					

Table 2.7 – Summary of evidence from study outcomes and GRADE assessment for all studies

2.4.4.2 – Results Grouped by Muscle

As outlined in section 2.4.2.3, three muscle groups were investigated within the studies in this review, the ES, the paraspinal muscles and the multifidus. Study outcomes were reported for the ES a total of 24 times, with results deriving from 72 comparisons between groups across 12 tasks. The paraspinal muscles had a total of 12 study outcomes from 28 comparisons across seven tasks. The *multifidus* had 15 study outcomes from 47 comparisons of muscle activity over 12 tasks (Table 2.8).

Trunk flexion was most commonly reported task across all muscle groupings, however a similar number of studies investigated combined flexion and extension in the *multifidus*. Four studies in the paraspinal muscles, three studies in the ES, and nine studies in the *multifidus* were investigated by one study apiece. Lumbar pelvic tilt was the only task not investigated in the ES or multifidus; however, five tasks were not investigated in the paraspinal muscles.

Task Outline	Paraspinal Muscles					Erector Spinae					*Multifidus*				
	Studies (Outcomes)	Majority Muscle Activity				Studies (Outcomes)	Majority Muscle Activity				Studies (Outcomes)	Majority Muscle Activity			
		+	<>	-	Mixed		+	<>	-	Mixed		+	<>	-	Mixed
Trunk Flexion	4 (11)	1	2	-	1	4 (7)	2	2	-	-	3 (11)	-	2	1	-
Trunk Extension	1 (2)	-	1	-	-	2 (2)	-	-	2	-	1 (4)	-	1	-	-
Seated Trunk Flexion	-	-	-	-	-	2 (3)	-	1	1	-	1 (2)	-	-	-	1
Seated Trunk Extension	2 (6)	-	2	-	-	1 (2)	-	-	1	-	1 (2)	-	1	-	-
Prone Trunk Extension	-	-	-	-	-	1 (3)	-	1	-	-	1 (1)	1	-	-	-
Lateral Trunk Flexion	-	-	-	-	-	1 (2)	-	1	-	-	1 (8)	-	1	-	-
Left Axial Rotation	1 (2)	-	-	-	1	3 (13)	-	3	-	-	1 (4)	-	1	-	-
Right Axial Rotation	1 (2)	-	1	-	-	3 (13)	-	3	-	-	1 (4)	-	1	-	-
Lifting	-	-	-	-	-	3 (18)	1	2	-	-	1 (4)	1	-	-	-
Lumbar Pelvic Tilt	2 (4)	-	1	-	1	-	-	-	-	-	-	-	-	-	-
Flexion and Extension	1 (1)	1	-	-	-	2 (4)	-	2	-	-	3 (6)	-	2	-	1
Combined Trunk Tasks	-	-	-	-	-	2 (5)	-	2	-	-	1 (1)	-	1	-	-
GRADE Assessment	**LOW**					**VERY LOW**					**VERY LOW**				
GRADE Assessment Criteria (score)	Moderate risk of biases (+) Moderate publication biases (-) Inconsistently defined precision (-) Moderately consistent results Direct outcomes (+)					High risk of biases (-) Moderate publication biases (-) Inconsistently defined precision (-) Inconsistent Results (-) Direct outcomes (+)					High risk of biases (-) Moderate publication biases (-) Inconsistently defined precision (-) Moderately consistent results Direct outcomes (+)				

Table 2.8 – Summary of evidence from study outcomes and GRADE assessment for each group, split by muscle subgroup indicating greater (+), less (-), no difference (< >) in muscle activity or a mixed majority of results.

2.4.4.2.1 – Paraspinal Muscles

The magnitude of muscle activity in the paraspinal muscles was investigated in six studies (209 participants) (Adams, 2006, Ambroz et al., 2000, Cohen et al., 1986, Collins et al., 1982, Kankaanpaa et al., 2005, Kankaanpaa et al., 1998). Within the results of these studies for each task, results from seven study outcomes identified no differences in muscle activity between groups (studies investigated multiple tasks). Two further study outcomes reported a majority of results which indicated greater paraspinal muscle activity in individuals with CNSLBP and outcomes from three studies reported mixed results (Fig. 2.3).

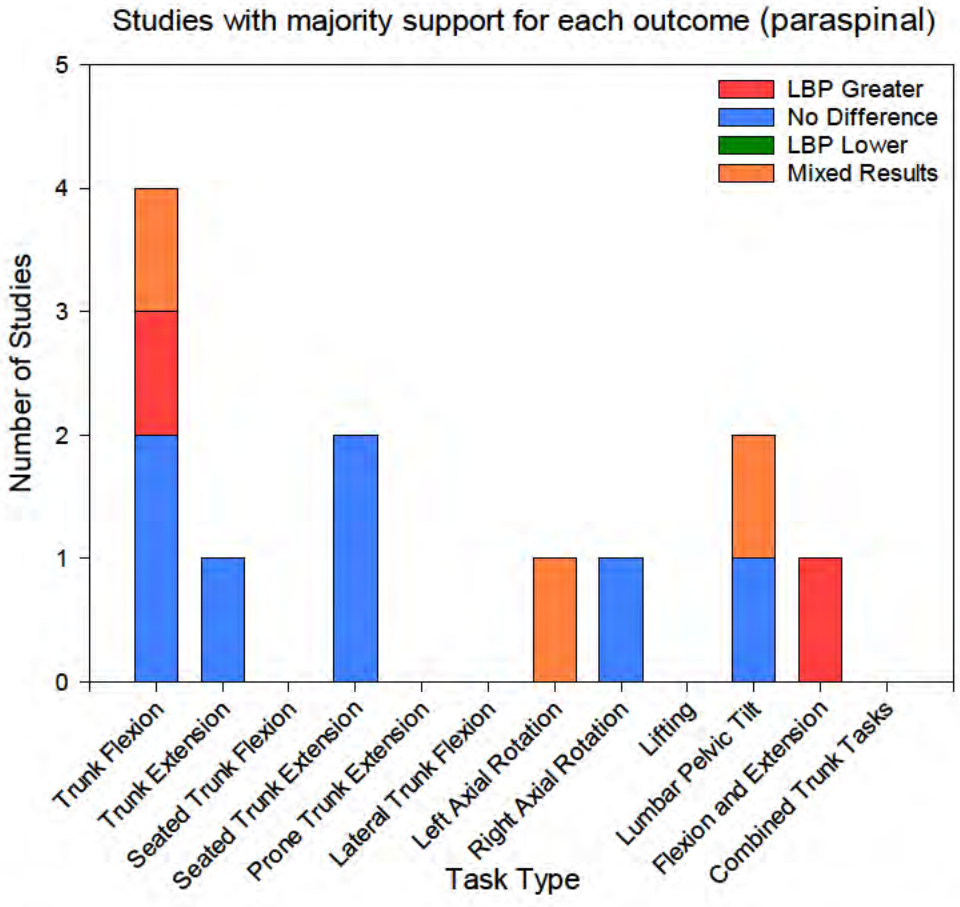


Fig. 2.3 – Muscle activity outcomes for the paraspinal muscles, grouped by the task completed.

In the paraspinal muscles, trunk flexion results were the most varied as the four studies which investigated this outcome were split between no differences (n=2), greater (n=1) and mixed (n=1, no difference/greater). Combined flexion and extension (n=1) indicated greater muscle activity in the paraspinal muscles. However, studies which investigated trunk extension, standing (n=1) and seated (n=2), and right axial rotation (n=1) all reported no differences in muscle activity between groups.

The cumulative evidence for the magnitude of muscle activity in individuals with CNSLBP in the paraspinal muscle group was determined to be of low quality. There were moderate risks of bias and reasonably consistent results among included studies, however publication biases and inconsistent precision prevented further increases. In the paraspinal muscles subgroup, a low quality of evidence from six studies supported a conclusion of no differences in muscle activity between groups.

2.4.4.2.2 – *Multifidus*

The magnitude of muscle activity in the *multifidus* was investigated in 11 studies (821 participants) (Danneels et al., 2002, de Aquino Nava et al., 2017, Descarreaux et al., 2007, Djordjevic et al., 2015, Du et al., 2018, Ershad et al., 2009, Kienbacher et al., 2017, Lima et al., 2018, Ng et al., 2002a, Rossi et al., 2017, Yang, 2018). No differences in muscle activity were identified across ten study outcomes. Greater activity in the CNSLBP group was only identified in two study outcomes, lesser activity in one, and mixed results were identified in two outcomes (Fig. 2.4).

A majority of tasks which investigated the magnitude of muscle activity in the multifidus were only reported by one study each, with only trunk flexion (n=3) and combined flexion and extension (n=3) investigated by more than one study. In these tasks,

no differences were identified in two study outcomes apiece, and the remaining studies identified lower activity (trunk flexion) and mixed results (no difference/greater; flexion and extension). Within this muscle, no differences in muscle activity were reported for seated and standing trunk extension, however greater muscle activity was identified for prone trunk extension, and lifting (which involved extension components).

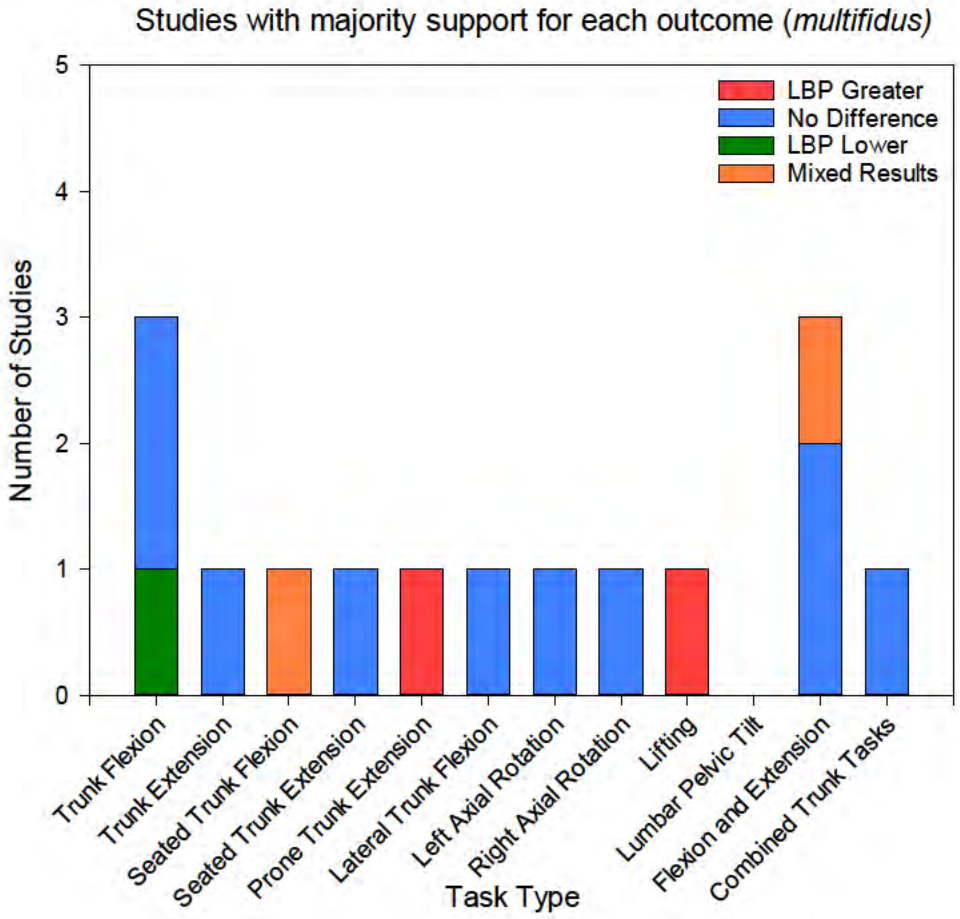


Fig. 2.4 – Muscle activity outcomes for the *multifidus*, grouped by the task completed.

The cumulative quality of evidence for muscle activity in the *multifidus* is of very low quality. While there was moderate consistency in the results of studies, a majority of outcomes were reported from n=1 and there was a high risk of bias among most studies.

In the multifidus subgroup, a very low quality of evidence from 11 studies supported a conclusion of no differences in muscle activity between groups.

2.4.4.2.3 – Erector Spinae

The magnitude of muscle activity in the ES was investigated in 13 studies (669 participants) (Cimbiz, 2006, Danneels et al., 2002, de Aquino Nava et al., 2017, Descarreaux et al., 2007, Ershad et al., 2009, Falla et al., 2014, Lariviere et al., 2002b, Lima et al., 2018, Lin et al., 2001, Ng et al., 2002a, Pirouzi et al., 2006, Rossi et al., 2017, Shirado et al., 1995). No differences were identified between groups in 17 study outcomes. The remaining study outcomes were split between greater activity (n=3) and lesser activity (n=4) in the CNSLBP participants. (Fig. 2.5).

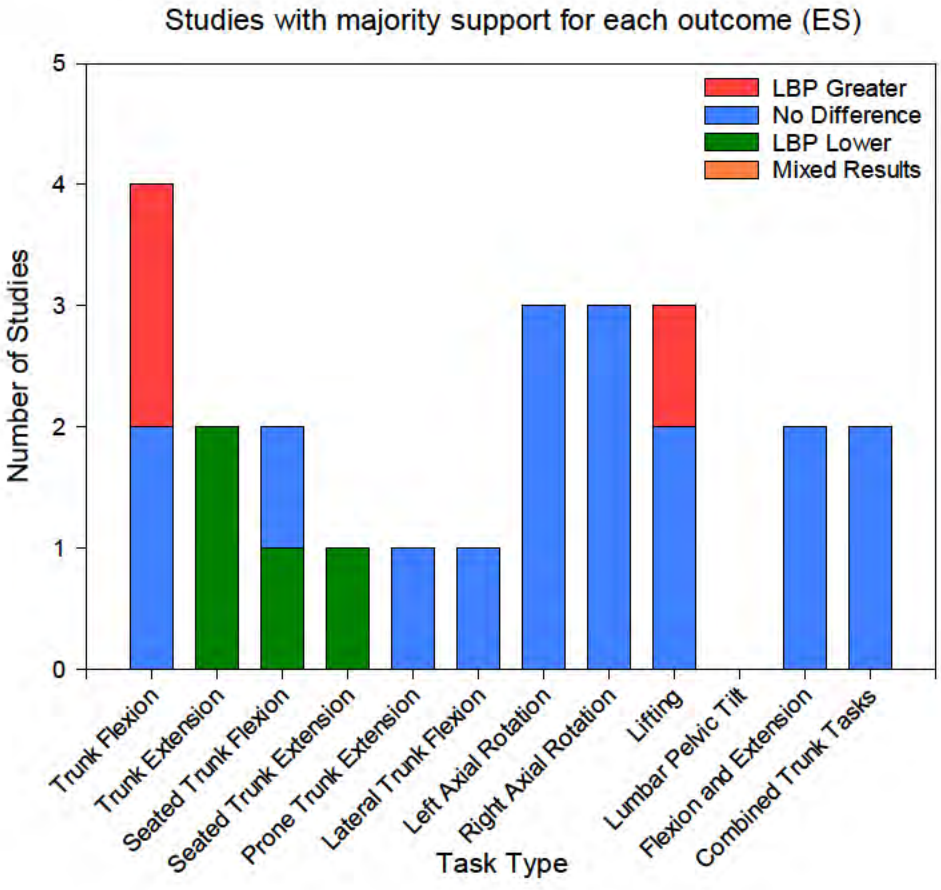


Fig. 2.5 - Muscle activity outcomes for the *ES*, grouped by the task completed.

The outcomes of studies which investigated trunk flexion in the ES were split between no differences (n=2) and greater activity in CNSLBP (n=2). Further evidence supporting greater activity in the ES for the CNSLBP group was identified during lifting; one study indicated greater activity, and two showed no differences. All studies which investigated trunk extension (n=2) and seated trunk flexion (n=1) identified lower activity, but no differences were identified during prone trunk extension (n=1). Lower activity was also identified in seated trunk flexion (n=1), but a further study reported no differences (n=1).

The cumulative evidence for muscle activity in the ES was of very low quality. The results in this muscle were moderately consistent, however the studies exhibited high risk of biases and publication biases. In the ES subgroup, a very low quality of evidence from 13 studies supported a conclusion of no differences in between groups.

2.4.4.3 – Results Grouped by Contraction Type

Two different contraction groupings were investigated across the studies included in this review as detailed in section 2.4.2.2; static/isometric and dynamic/isotonic. Static/isometric tasks were investigated in 18 study outcomes derived from 74 comparisons of activity across eight tasks. Dynamic/isotonic tasks had a total of 25 study outcomes reported from 73 comparisons of muscle activity across ten tasks (Table 2.9).

Trunk flexion was the most common task in both groups, with a similar number of studies investigating trunk extension in the dynamic/isotonic group. Lifting was the most comprehensively investigated task, with 22 individual comparisons investigating this across three studies in the dynamic/isotonic group. Two tasks in each grouping were only investigated by one study each.

Task Outline	Static/Isometric					Dynamic/Isotonic				
	Number of Studies (Outcomes)	Majority Muscle Activity				Number of Studies (Outcomes)	Majority Muscle Activity			
		+	< >	-	Mixed		+	< >	-	Mixed
Trunk Flexion	6 (20)	2	3	1	-	5 (9)	2	2	-	1
Trunk Extension	-	-	-	-	-	4 (8)	-	2	2	-
Seated Trunk Flexion	1 (4)	-	-	1	-	1 (1)	-	1	-	-
Seated Trunk Extension	2 (8)	-	1	-	1	1 (2)	-	1	-	-
Prone Trunk Extension	2 (4)	1	1	-	-	-	-	-	-	-
Lateral Trunk Flexion	-	-	-	-	-	2 (10)	-	2	-	-
Left Axial Rotation	2 (16)	-	2	-	-	2 (3)	-	1	-	1
Right Axial Rotation	2 (16)	-	2	-	-	2 (3)	-	2	-	-
Lifting	-	-	-	-	-	3 (22)	1	2	-	-
Lumbar Pelvic Tilt	2 (4)	-	1	-	1	-	-	-	-	-
Flexion and Extension	1 (2)	-	1	-	-	3 (9)	1	1	-	1
Combined Trunk Tasks	-	-	-	-	-	2 (6)	-	2	-	-
GRADE Assessment	**VERY LOW**					**VERY LOW**				
GRADE Assessment Criteria (score)	Moderate to high risk of biases Moderate publication biases (-) Inconsistently defined precision (-) Inconsistent results (-) Direct outcomes (+)					High risk of biases (-) Moderate publication biases (-) Inconsistently defined precision (-) Inconsistent results (-) Direct outcomes (+)				

Table 2.9 – Summary of evidence from study outcomes and GRADE assessment for each group, split by contraction type subgroup indicating greater (+), less (-), no difference (< >) in muscle activity or a mixed majority of results.

2.4.4.3.1 – Static/Isometric Tasks

The magnitude of muscle activity was reported during static/isometric tasks in 13 studies (n=529) (Ambroz et al., 2000, Cimbiz, 2006, Cohen et al., 1986, Collins et al., 1982, Descarreaux et al., 2007, Djordjevic et al., 2015, Ershad et al., 2009, Kankaanpaa et al., 1998, Ng et al., 2002a, Pirouzi et al., 2006, Rossi et al., 2017, Shirado et al., 1995, Yang, 2018). No differences in muscle activity were identified in eight study outcomes, and mixed results were identified in two outcomes. Greater muscle activity was identified in the CNSLBP group in three studies, and lower activity in two studies (Fig. 2.6).

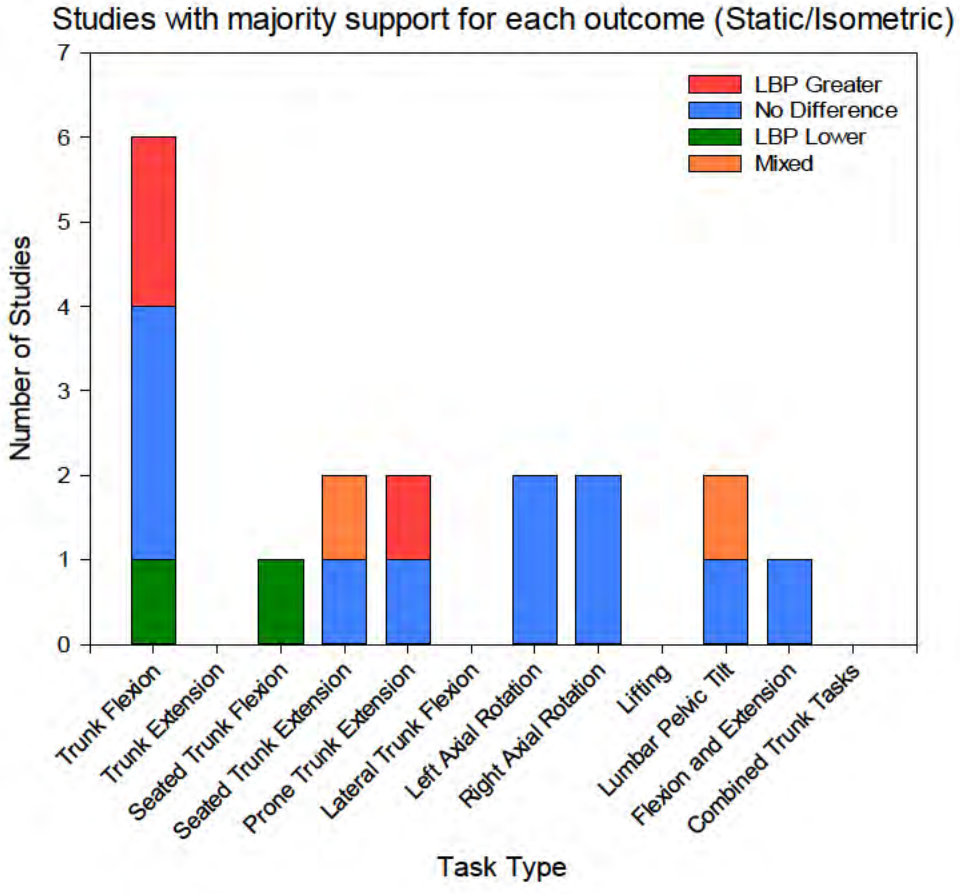


Fig. 2.6 - Muscle activity outcomes for static/isometric contractions, grouped by the task completed.

The results for static/isometric trunk flexion demonstrated the greatest variation in the results, with study outcomes reporting lower activity (n=1), no differences (n=3) and greater activity (n=2) in participants with CNSLBP. Seated flexion was less variable, however it was only investigated by one study which identified lower activity. Left and right axial rotation were investigated in two study outcomes apiece and results from all outcomes indicated no differences for either task.

The cumulative evidence for the magnitude of muscle activity in individuals with CNSLBP during static/isometric contractions was very low quality. This score is due in part to the inconsistent results and high risk of biases exhibited in most studies included in this grouping. In the static/isometric subgroup, a very low quality of evidence from 13 studies supported a conclusion of no differences in muscle activity between groups.

2.4.4.3.2 – Dynamic/Isotonic Tasks

A total of 13 studies (n=982) investigated the magnitude of muscle activity between groups during dynamic/isotonic tasks (Adams, 2006, Ambroz et al., 2000, Cimbiz, 2006, Danneels et al., 2002, de Aquino Nava et al., 2017, Du et al., 2018, Falla et al., 2014, Kankaanpaa et al., 2005, Kienbacher et al., 2017, Lariviere et al., 2002b, Lima et al., 2018, Lin et al., 2001, Shirado et al., 1995). No differences were identified in muscle activity across 16 study outcomes, with a further three studies reporting mixed results. Four study outcomes reported greater muscle activity in participants with CNSLBP, and just two study outcomes reported lower activity (Fig. 2.7).

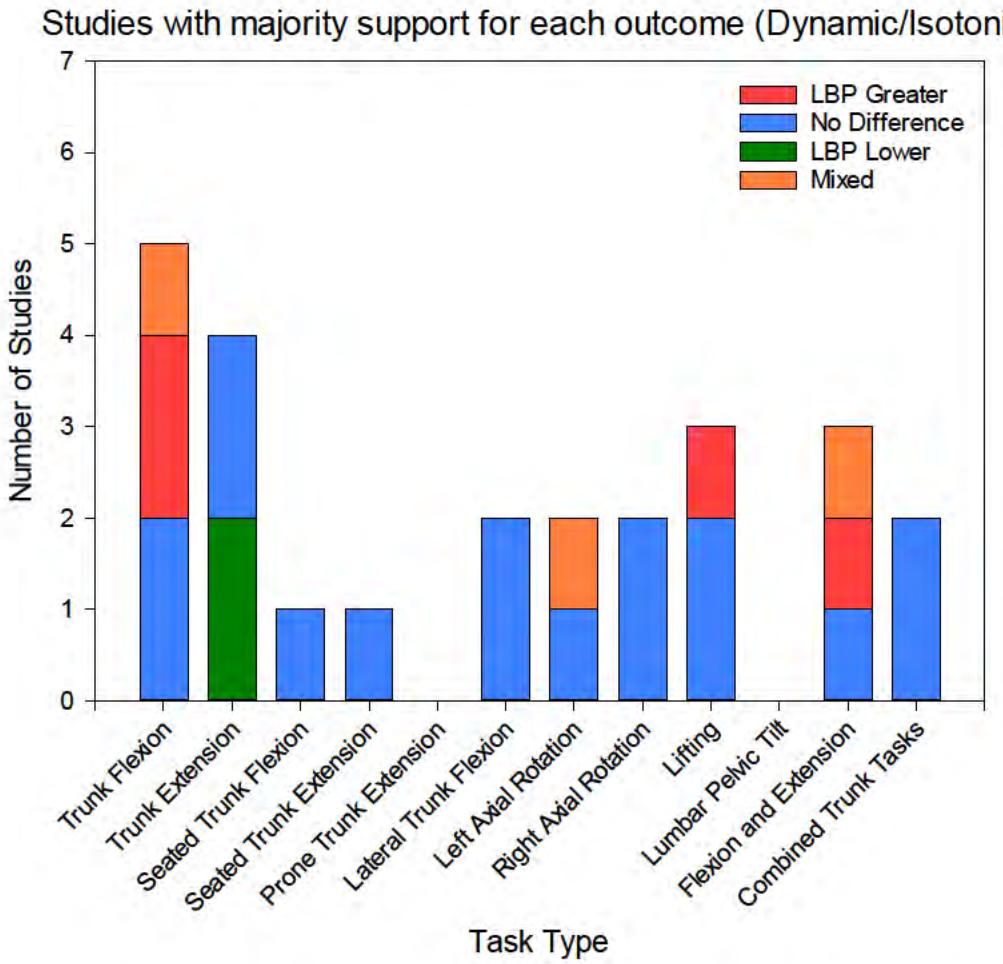


Fig. 2.7 - Muscle activity outcomes for dynamic/isotonic contractions, grouped by the task completed.

The results for muscle activity in trunk flexion and extension appear to be broadly opposing. Studies which investigated trunk flexion reported greater activity (n=2), no difference (n=2) and mixed results (n=1, greater/no difference). Conversely, muscle activity reported during trunk extension was found to be lower (n=2) or demonstrated no differences (n=2). This relationship did not extend to seated tasks, with both seated flexion and extension reporting no differences from one study each. Other tasks with include flexion to some degree also reported greater muscle activity, including lifting and flexion and extension. In lifting, greater activity

(n=1) and no differences were reported (n=2); in flexion and extension, no differences (n=1), greater activity (n=1) and mixed results (n=1; greater/no difference) were reported.

The cumulative quality of evidence for the magnitude of muscle activity during dynamic/isotonic contractions was very low. The results were inconsistent in this grouping, with several examples of mixed results, and the risk of biases among included studies was high. In the dynamic/isotonic subgroup, a very low quality of evidence from 13 studies supported a conclusion of no differences in muscle activity between groups.

2.4.5 – Strength of Cumulative Evidence

The overall quality of cumulative evidence within this review was very low, with only one subgrouping of data presenting low quality data (paraspinal muscles, section 2.4.8.2.1). The GRADE ratings and rationales for each grouping of data are reported in Table 2.10.

This assessment of the cumulative data quality was based partially on the observational nature of the studies; high risk of biases among included studies; and variability in reported results. All studies had similar publication biases, arising from the non-publication of studies identified in the grey literature search, with eight conference abstracts not linked to any published studies. Additionally, seven studies were excluded based on ambiguity of the reported CNSLBP sample inclusion criteria (Chiou et al., 1999, Finneran et al., 2003, Grabiner et al., 1992, Kim et al., 2013, Kumar and Prasad, 2010, Kuriyama and Ito, 2005, Linsinski, 2000). All studies were scored nearly identically for precision, while the reporting of significant p-values was prevalent, any insignificant results were identified as (>0.05) and very few reported confidence intervals or effect sizes alongside results.

Grouping		Number of Studies	Group Comparison Outcomes			NOS Ratings		GRADE	
			+	< >	-			Level	Justification
All Studies n=1355		23	25	107	15	Good	1	Very Low	High risk of biases (-) Moderate publication biases (-) Inconsistently defined precision (-) Inconsistent results (-) Direct outcomes (+)
						Fair	5		
						Poor	17		
Muscle	Paraspinal Muscles n=209	13	15	50	7	Good	1	Low	Moderate risk of biases (+) Moderate publication biases (-) Inconsistently defined precision (-) Moderately consistent results Direct outcomes (+)
						Fair	3		
						Poor	2		
	Multifidus n=821	11	7	35	5	Good	-	Very Low	High risk of biases (-) Moderate publication biases (-) Inconsistently defined precision (-) Inconsistent Results (-) Direct outcomes (+)
						Fair	1		
						Poor	10		
	Erector Spinae n=669	6	4	22	2	Good	-	Very Low	High risk of biases (-) Moderate publication biases (-) Inconsistently defined precision (-) Moderately consistent results Direct outcomes (+)
						Fair	2		
						Poor	11		

Contraction Type	Static/Isometric n=529	13	7	58	11	Good	1	Very Low	Moderate to high risk of biases Moderate publication biases (-) Inconsistently defined precision (-) Inconsistent results (-) Direct outcomes (+)
						Fair	3		
						Poor	9		
	Dynamic/Isotonic n=982	13	19	51	3	Good	-	Very Low	High risk of biases (-) Moderate publication biases (-) Inconsistently defined precision (-) Inconsistent results (-) Direct outcomes (+)
						Fair	3		
						Poor	10		

Table 2.10 – Summary of muscle activity comparisons, risk of bias outcomes and GRADE rating for each grouping of studies, GRADE outcomes have been marked with (–) where decreases, and (+) where increases have been designated.

2.5 – Discussion

2.5.1 – Summary of Evidence

This is the first comprehensive and methodologically rigorous review to investigate the magnitude of muscle activity, and alterations therein, in the presence of CNSLBP. A total of 23 studies were identified which used back-specific tasks to investigate this, and a majority of results indicated that there were no differences in muscle activity between groups. However, most reviewed studies exhibited high risk of biases, with key criteria underlying this rating including poor task reporting and standardisation, and unclear descriptions of control participant recruitment. Accordingly, this review identified a weak level of evidence supporting no differences in muscle activity in people with CNSLBP during back-specific functional tasks (Guyatt et al., 2008, Guyatt et al., 2011a, Guyatt et al., 2011b, Guyatt et al., 2011c, Guyatt et al., 2011d, Guyatt et al., 2011e).

2.5.1.1 – Muscle Activity Evidence

At the broadest level, across the 23 studies included within this review, a very low quality of evidence supported no differences in muscle activity. Prior to subgrouping, while some tasks (*e.g.* trunk flexion) presented more mixed outcomes, a majority of study outcomes identified no differences in the magnitude of muscle activity between pain free controls and people with CNSLBP. This result was also consistent when considering the net individual comparisons of muscle activity between groups within studies.

2.5.1.2 – Evidence in Muscle Subgroups

There was a low quality of evidence within the paraspinal muscle subgroup which indicated no differences in muscle activity in people with CNSLBP. In the subgroupings for the *multifidus* and the ES there was a very low quality of evidence which identified no differences in activity between groups. However, the results for the ES subgroup were less uniform than in other groupings. Within the subgroup of studies which investigated ES activity, a majority of evidence for extension tasks indicated that there was less activation in individuals with CNSLBP, and conversely during standing trunk flexion an equal amount of evidence for greater ES activation (see Fig. 2.5). For the paraspinal muscles and *multifidus* these tasks, as with all others, had a majority of results indicating no differences in muscle activity between groups.

As discussed in Chapter one, the ES is thought to underlie the majority of gross lumbar movements (Mawston and Boocock, 2015). The ES has been identified as the most biomechanically favourable muscle for these tasks, due to its comparatively long lever arm of all trunk extensors during standing (Daggfeldt and Thorstensson, 2003). Therefore, the function is believed to be primarily the production of gross trunk movements, compared to the *multifidus*, which is thought to principally function as an intersegmental stabiliser (Mawston and Boocock, 2015). Therefore, it is possible that these differences in muscle activity might reflect the more functional use of the ES during trunk flexion and extension. This functional link is reflected in the included publications, with studies which investigate the ES often focussing on activation during specific functional tasks, such as lifting and axial rotation (Falla et al., 2014, Lariviere et al., 2002b, Ng et al., 2002b, Ng et al., 2002a), whereas studies which investigated the multifidus were broadly spread across all tasks in a non-specific way.

2.5.1.3 – Evidence in Contraction Type Subgroups

The cumulative quality of evidence in subgroupings of studies which investigated muscle activity during static/isometric and dynamic/isotonic tasks was very low in both groups. A majority of studies in both subgroups identified no differences in muscle activity between groups, however slightly more studies deviated from this during dynamic/isotonic tasks. In the dynamic/isotonic subgroup, trunk flexion and extension were demonstrated to have opposing results where groups were found to have different muscle activity. Studies which identified differences in trunk flexion indicated greater activity during trunk flexion (n=2/5) and less activity during trunk extension (n=2/4). Trunk flexion and extension and lifting tasks, which consisted of weighted trunk flexion and extension, also had some evidence of greater activation in the CNSLBP group (n=1/3 per task). A similar pattern was identified during static/isometric trunk flexion, with two studies identifying greater muscle activity in the CNSLBP group, however this was countered with further results of no difference (n=1) and less activity (n=1) in this task.

These results, while from different subgroupings, could be interpreted to be somewhat complementary, suggesting a larger eccentric contraction during flexion, but less relative activity during concentric extension elements. This is most clearly identified in the dynamic/isotonic subgroups and may be suggestive of a more constant contraction strategy in CNSLBP, which is unaffected by the changing biomechanical demands from extension to flexion. This finding would be in line with common perceptions of muscle activity, with continual activation of the paraspinal muscles in people with CNSLBP typically highlighted during maximal flexion in a flexion-extension task (Ambroz et al., 2000, Shirado et al., 1995, Murillo et al., 2019b). It is important to note that within this review, there was little evidence reported to support this finding in tests of combined flexion-extension, however these tasks

considered the entire task and so the opposing activations described here might have been lost during the averaging process. However, in included studies where this effect was split into component parts, did identify this characteristic pattern (Ambroz et al., 2000, Shirado et al., 1995).

2.5.1.4 – Evidence Related to Pain Outcomes

As the methodological focus was on people with CNSLBP in studies included within this review, the lack of consistent pain outcome reporting was unexpected. The secondary outcome for this review intended to correlate any differences in muscle activity with changes in pain symptoms over the task duration. However, initial and average pain prior to data collection were demonstrated to be reported with varying consistency, and far fewer studies reported pain or any other PROMs following task completion (Kyte et al., 2015). As such it was not possible to identify changes in pain, or relate these to differences in muscle activity due to this inconsistent reporting. For example, the average pain in the study by Kienbacher et al. (2017) was recorded as "<30mm" in the 12 weeks prior to testing, Djordjevic et al. (2015) however detailed a mean pain of 5.25±2.74/10 over the previous week. While these scales are similar and can be comparable, the period considered differs significantly and evidence has shown that there can also be significant differences between the PNRS and VAS scales which hinders direct comparison (Karcioglu et al., 2018). These and other similar inconsistencies mean that it is not possible to accurately characterise the duration or severity of CNSLBP symptoms across studies further than confirming the 3-month minimum criteria for eligibility.

Nonetheless, for studies where levels of pain related the CNSLBP symptoms were reported, the included participants represented a broad range of pain levels. With a full range

of mild – moderate scores reported for both average pain before testing and pain on the day of data collection (Breivik et al., 2008). it is thought that the level of pain in this sample would be generally representative of people with CNSLBP without severe disabling symptoms (Carlesso et al., 2018).

2.5.2 – Limitations in the Evidence

The majority of results indicate that there is no difference in paraspinal muscle activity in individuals with CNSLBP, however the results of individuals studies are mixed. One of the reasons for this disparity between individual studies might be inconsistencies in the methodology used. This section will consider these inconsistencies and other methodological considerations which might underlie the mixed results.

2.5.2.1 – Risk of Bias within Studies

The conclusions of this review indicate no consistent differences in muscle activity between groups, however it has been identified that these results may be influenced by the very low quality of the cumulative evidence and high risk of bias among studies. As highlighted in Table 2.6, there are elements of reporting in studies which have investigated muscle activity which require strengthening in order to progress the field by producing high-quality literature with a low risk of bias (Wells, Accessed 2018). Within this review, no studies reported the use of the STrengthening the Reporting of OBservational studies in Epidemiology (STROBE) checklist, a tool specifically designed to improve methodological rigour in reporting of observational studies (von Elm et al., 2008). The use of this tool would strengthen the reporting of these studies and reduce the bias identified in the literature. Specifically, for the studies

within this review, this could be achieved through increasing the rigour in task descriptions, employing the use of standardised electrode placements for measurement, and providing detailed information regarding the control sample recruitment. By strengthening the methodological reporting and using more consistent placement of electrodes, it is expected that the variation in results between individual studies might decrease and allow stronger conclusions to be drawn.

2.5.2.2 – Limitations in Study Objectives

In studies which investigated the magnitude of muscle activity in individuals with CNSLBP, a very low quality of evidence identified no differences in the magnitude of muscle activity compared to pain free controls. This result is somewhat unexpected in light of the continued focus for research in this area (Martinez-Valdes et al., 2019, Murillo et al., 2019b, Psycharakis et al., 2019). However, in these studies, as in a majority of studies in this review, the primary objective was not directly related to the muscle activity outcome. As such, in some instances the methodology surrounding this outcome was less comprehensive than that in place to measure the primary objective. One example from this review is the work by Kankaanpaa et al. (2005), this study investigated muscle oxygenation and activity during trunk extension. In this study, the muscle activity outcome was reported during only the first five seconds (s) of the sustained endurance task, with alternative outcomes (*e.g.* the change in myoelectrical fatigue and muscle oxygenation) measured throughout the task. In this instance, an initial lack of differences in muscle activity between groups was used as a 'validation' of the use of the fatigue slope to assess alternative outcomes (Kankaanpaa et al., 2005). This interpretation of the purposes underlying the measurement of muscle activity might be shared across studies; with

the activity measured and reported briefly as a means to provide justification for further analysis.

2.5.2.4 – Limitations in Task Description

Within this review, the methodologies of individual tasks were distilled to the primary movements completed, however these occasionally did not correlate with the published descriptions. For example, two studies included in this review described near identical tasks in which the trunk was maintained at 30^{o} flexion with a weight held in the hands (Ershad et al., 2009, Yang, 2018). However, in published descriptions, one of these tasks was described as 'weighted flexion' and the other as 'stooped lifting'. Both tasks were classified in this review as flexion as the signals were recorded in static postures and other lifting tasks in this review all involved dynamic recordings.

Further, the accurate inclusion of results for individual tasks has been hindered by the averaging or the non-reporting of results. The moniker 'Dynamic Trunk Tasks' was used as a group descriptor where all others fell short, and included an instance of several tasks being combined and the mean activity across all being reported (Danneels et al., 2002). In this example, the tasks were all back specific so the combined results could be included, however a further result from this study which averaged results for prone back extension and hip extension was excluded from this synthesis (Danneels et al., 2002). Conversely, another means which was used to simplify a complex data-set included intentionally not-reporting the results from selected tasks for brevity (Collins et al., 1982). These examples of unreliable reporting of task descriptions and outcomes highlights a complex issue which might make it difficult to synthesise results from individual publications.

2.5.2.3 – Limitations in EMG

Electrode placement is an instance whereby inaccuracies in comparisons across studies could have been introduced. Despite the consensus statements publicising the need for standardised placement of electrodes across studies (Hermens et al., 2000, Hodges, 2020), within this review of 15 instances where the ES was recorded across 13 studies, there was consistency in reported placement in one instance between two studies. The investigations by Ershad et al. (2009) and Lariviere et al. (2002b) placed electrodes 3cm lateral to the L3 spinous process for the ES. One further study (Pirouzi et al., 2006) specifically reported the use of a standardised electrode placement the ES (Criswell, 2010), however this was not adopted by any other studies in this review. Placements of electrodes to measure activity in the *multifidus* showed greater similarities, with a number of studies using the Surface EMG for Non-invasive Assessment of Muscles (SENAIM) guidelines for the placement of electrodes (de Aquino Nava et al., 2017, Djordjevic et al., 2015, Kienbacher et al., 2017, Lima et al., 2018, Ng et al., 2002a, Rossi et al., 2017). The paraspinal muscle electrode placement was the most varied, likely as it reflected placement to record both the *multifidus* and the lumbar ES, as highlighted by the placements of electrodes in the study by Collins et al. (1982). In this study electrodes were placed 2cm lateral of the L5 and L2 spinous processes, and similar locations were later used to record activity from the *multifidus* (Rossi et al., 2017) and the ES (Lima et al., 2018) respectively. Measurement of generic paraspinal muscle activity is less common in more recent studies, with a majority of studies using this label published prior to the year 2000, and none more recent than 2006.

Only one study included within this review incorporated HDEMG to investigate muscle activity (Falla et al., 2014). This technique investigates muscle activity across a region rather

than between two points and could facilitate more detailed investigations. Falla and colleagues reported a majority result of no differences in this study, albeit with greater activity in the CNSLBP group identified in individual comparisons of activity at the end of the task. Within this study however, the primary outcome involved the topographical analysis of activity and identified less redistribution of muscle activity across the muscle in the cranio-caudal axis in the CNSLBP groups (Falla et al., 2014). This finding suggests that while there might be no differences in the magnitude of activity, it is possible that more detailed investigation of muscle activation may identify differences in the distribution of activity.

2.5.2.5 – Publication Biases

As detailed in section 2.4.7, publication biases were identified within the literature search underlying this review (Guyatt et al., 2011d). Eight conference abstracts were identified which were unable to be linked to any published material, including instances where the authors were uncontactable, and instances of authors reporting not publishing results. Further, seven publications were excluded due to ambiguity in the CNSLBP criteria, as the authors were uncontactable for clarification.

2.5.3 – Review Strengths and Limitations

This is the first comprehensive systematic review to synthesise the results of studies, which investigated the influence of CNSLBP on the magnitude of lumbar paraspinal muscle activity, across a variety of muscles and back specific tasks. This review was rigorous and closely followed a pre-published, peer-reviewed and registered protocol to reduce bias.

Within the studies included in this review, it was noted that there is a growing body of evidence supporting altered distribution of activity in the lumbar musculature related to CNSLBP. While this outcome was outside of the aims of this review, it may have added some further evidence to contextualise HDEMG results.

2.5.4 – Implications for Future Research and Practice

The evidence within this review was primarily of very low quality, however no consistent differences in the magnitude of muscle activity between individuals with and without CNSLBP were identified. Alongside the need for more methodologically rigorous studies to confirm this outcome, this result indicates that the magnitude of muscle activity may not accurately characterise the complexity of human muscle activation. As such, it is suggested that future research may focus investigation on techniques which allow for the identification of more subtle changes in muscle activity, for example the use of HDEMG as in Falla et al. (2014).

In this review, the level of cumulative evidence was very low in all but one of the groupings considered. Accordingly, the following suggestions have been made to improve the quality of future research. It is suggested that a more consistent and standardised placement of electrodes be used to record activity, particularly in the ES. Additionally, the perceived risk of biases in study reporting could be reduced by including more thorough and standardised task descriptions, greater detail in reported participant inclusion criteria and consistent reporting of control sample recruitment. This could be achieved through the adoption of rigorous reporting methodology, such as the use of the STROBE checklist (von Elm et al., 2008).

2.6 – Conclusions

Due to the very low quality of cumulative evidence, a weak recommendation can be made from this review that there are no consistent differences in the magnitude of muscle activity in individuals with CNSLBP. Within the subgroup analyses, a very low quality of data was identified for all but the paraspinal muscle subgroup (low quality), and analyses in all subgroups indicated that there were no differences in muscle activity between groups. Due to the low and very low qualities of evidence, weak overall recommendations for all subgroups in this review also indicate that there are no differences in muscle activity in people with CNSLBP.

While these results are fairly consistent across included studies, the very low quality of the cumulative evidence, and heterogeneity in outcomes has identified areas for further research. The most consistent differences were identified during trunk flexion and trunk extension, but few studies have investigated prone or seated extension, highlighting this as an area which requires further high-quality research. There was some variation in muscle activity identified in studies which investigated the ES, highlighting this muscle as an area for further investigation. There was no significant differences in the results identified from completing dynamic/isotonic tasks or static/isometric tasks; indicating that further research is required in both contraction types. Finally, the studies in this review primarily used bipolar EMG, when it was used, HDEMG identified no differences in the magnitude of muscle activity, however differences in the distribution of activity were identified. Thus, it is suggested that further research using this technique may facilitate the identification of novel differences in muscle activity in people with CNSLBP. Therefore, the remainder of this thesis will focus on muscle activity measured using HDEMG overlying the ES during a mixture of static and dynamic tasks, centred around trunk flexion and extension.

CHAPTER 3

VARIATION IN THE SPATIAL DISTRIBUTION OF ERECTOR SPINAE ACTIVITY DURING A LUMBAR ENDURANCE TASK IN PEOPLE WITH LOW BACK PAIN: A CROSS-SECTIONAL STUDY

This Chapter reports in full a manuscript which has been published previously (Sanderson et al., 2019b). Changes have been made in the text of this Chapter for the purposes of a thesis, specifically;

- The introduction has been edited to reflect the content of previous Chapters in this thesis and avoid repetition
- Areas of the methodology have been expanded upon to elaborate on the rationale underlying methodological decisions
- The discussion and conclusion have been edited to increase cohesion between linked studies in later Chapters.

However, the majority of the text in this Chapter reflects the published manuscript verbatim and has been reprinted with permission from Wiley.

Publications and Presentations

1. **Sanderson, A.**, Martinez-Valdes, E., Heneghan, N. R., Murillo, C., Rushton, A., Falla, D. 2019. Variation in the spatial distribution of erector spinae activity during a lumbar endurance task in people with low back pain. *J Anat,* 234**,** 532-542. **(Appendix 2)**

2. **Sanderson, A.,** Martinez-Valdes, E., Murillo, C., Heneghan, N.H., Rushton, A., Falla, D. A High-density EMG investigation of changes in erector spinae activity during an endurance task. 2017 Winter Meeting of the Anatomical Society. Dundee, United Kingdom, December 18-20, 2017.

3. **Sanderson, A.,** Martinez-Valdes, E., Murillo, C., Heneghan, N.H., Rushton, A., Falla, D. People with chronic low back pain show differences in the spatial distribution of erector spinae activity during an endurance task. XXII Congress of the International Society of Electrophysiology and Kinesiology (ISEK). Dublin, Ireland, June 30-2, 2018.

4. **Sanderson, A.,** Martinez-Valdes, E., Heneghan, N.H., Murillo, C., Rushton, A., Falla, D. Individuals with chronic low back pain demonstrate less diffused muscle activation in the lumbar erector spinae when completing an endurance task. Society for Back Pain Research (SBPR). Groningen, Netherlands, November 15-16, 2018.

3 – Abstract

The results from Chapter two indicated that a very low quality of evidence identified few consistent differences in the magnitude of muscle activity in individuals with CNSLBP. However, subgroupings of studies identified a focus for additional, high-quality research to investigate flexion and extension movements in the ES. Thus, this Chapter reports a cross-sectional study which aimed to investigate the spatial distribution and redistribution of lumbar ES activity during a lumbar extension endurance task in people with CNSLBP (LBP group) and pain free controls (CON group). HDEMG was recorded using 13x5 electrode grids placed unilaterally over the lumbar ES (most painful/right hand side) while completing an Ito test to task failure. The RMS of the HDEMG signals was computed, a topographical map of the EMG amplitude generated and the centre of the activity (centroid) determined throughout the task. The task was completed by 13 LBP (27.39 ±9.7 years) and 13 CON (26.46 ±5.0 years) participants. The LBP group demonstrated mild levels of pain (1.92 ±1.44/10) and minimal levels of disability (13.16% ±8%). Throughout the task, the centroid of the EMG amplitude map was found to be systematically more cranial ($P = 0.022$) for the LBP group compared to the CON group. Regression analysis showed that the extent of redistribution of ES activity was associated with longer endurance. These results show that people with CNSLBP utilised a different motor strategy to perform the endurance task, characterised by greater activation of more cranial regions of the ES and less redistribution of ES activity throughout the task. This study provides new insight into the functional activation of the lumbar ES and how it is modified when people have pain.

3.1 – Introduction

As discussed in the Chapter one, previous anatomical and biomechanical research on the lumbar ES has focussed on the relationship and the structure of different portions of this muscle group (Christophy et al., 2012, Bogduk, 1980, Bogduk, 2005). These descriptions concurred that while the portions of the ES muscle group have different origins and insertions, all play important roles in extending the lumbar spine during functional movements. In the systematic review completed in Chapter two, a very low quality of evidence identified no differences in the magnitude of muscle activity in individuals with CNSLBP. However, subgrouping of study results identified that further high-quality research considering muscle activity in the ES, and during flexion and extension tasks may identify differences in individuals with CNSLBP. Furthermore, it was highlighted that the use of HDEMG as a technique to evaluate muscle activity may facilitate the identification of novel differences between groups by considering the distribution of activity, presenting a promising direction for further research. Changes in the spatial distribution of muscle activity can be measured by HDEMG, and this outcome assessed by quantifying changes in the centroid of the HDEMG amplitude map (Falla et al., 2014, Madeleine et al., 2006, Farina et al., 2008, Falla et al., 2017, Gallina et al., 2013)

Lumbar muscle endurance tests such as the Ito test and the Sørenson test have been previously used to predict an increased risk of developing LBP (Alaranta et al., 1995, Demoulin et al., 2007, Luoto et al., 1995). The Sørenson test has commonly been used in previous studies to assess lumbar muscle endurance (Demoulin et al., 2007). However, when compared using bipolar EMG the Ito test was found to have greater specificity for the activation of the paraspinal musculature (Muller et al., 2010). In this study, the Sørenson test facilitated greater contraction

of the hip muscles and lower contraction of the ES when compared to the Ito technique. Therefore, to better assess the effects of low back pain on the lumbar musculature, the Ito test appears to be a more effective endurance task.

HDEMG was recently used during a lumbar endurance investigation to investigate the changes in lumbar ES activity in a CNSLBP population (Abboud et al., 2014). Participants completed a force-matching modified Sørenson test (lifting of the unsupported upper body with the legs affixed to a plinth), resisting a load cell around their shoulders which simulated 30% of their MVC. Increased variability in the position of the centroid of the EMG amplitude map was observed in the healthy controls compared to the CNSLBP group. Previous HDEMG investigations have also described an association between endurance time and the redistribution of muscle activity in the *trapezius* in asymptomatic participants (Farina et al., 2008). Despite these observations, the functional relevance of a change in the distribution of muscular activity remains unclear.

3.1.1 – Objectives

The objective of this Chapter is to investigate the spatial distribution, and redistribution, of unilateral lumbar ES activity in people with CNSLBP and pain-free controls during a static trunk extension task. This study stands to provide new insights into the functional activation of the lumbar ES muscle and how this activity differs in people with CNSLBP.

3.1.2 – Hypotheses

H3.1 - It was hypothesised that people with CNSLBP would engage different regions of the lumbar ES during isometric back extension, potentially reflecting less efficient activation of the lumbar ES.

H3.2 - Additionally, it was hypothesised that people with CNSLBP would show less redistribution of ES activity and that this would be associated with significantly lower endurance in this group.

3.2 – Methods

This study was classified as an observational, cross-sectional study and the study is reported in line with the STROBE statement. A cross-sectional design was chosen in lieu of a case-control design due to the differences highlighted between expected outcomes for these designs in Section 2.2.8 (Risk of bias in observational studies) (Luchini et al., 2017). According to the STROBE definitions for study designs (Vandenbroucke et al., 2007), both designs could apply to this study due to the inclusion of people with and without CNSLBP, and the single timepoint measurement of HDEMG. However, most case-control designs tend to assess the samples retrospectively and identify elements which might explain the existence of symptoms (Song and Chung, 2010). The purpose of this study is not to identify the cause of symptoms, instead to identify differences between groups, thus a cross-sectional design was selected.

Data collection took place in a laboratory within the Centre of Precision Rehabilitation for Spinal Pain (CPR Spine), University of Birmingham. Recruitment and data collection for this study was completed between September-December 2017 and data was collected within one session for each participant. Ethical approval was granted by the University of Birmingham Ethics Committee (ERN_17-0782, Appendix 8). Participants gave written informed consent prior to data collection and all procedures were completed in accordance with the Declaration of Helsinki.

3.2.1 – Participants

A convenience sample of participants with CNSLBP (LBP group) aged 20-55 years were recruited from the staff, students and community of the University of Birmingham, UK,

via posters and institution social media accounts. Due to the nature of the fatiguing task, it was decided that 55 would be the maximum age of participants eligible for this study. Eligibility criteria included non-specific CNSLBP which had persisted for at least half the days of the previous six months, exceeding the minimum definition for CNSLBP (Dionne et al., 2008). Consistent with a majority of previous studies reviewed in Chapter two, age and gender matched control participants (CON group) were recruited in the same way, and included if they had no history of CNSLBP or lower limb disorders.

Exclusion criteria for both groups comprised concurrent systemic issues including rheumatic and neuromuscular disorders, a history of chronic respiratory or neurological problems, spinal deformity or surgery, cardiovascular conditions, pregnancy, and healthcare management for CNSLBP in the previous six months (a requirement of the University Ethics Committee). To support a normal distribution for statistical analysis, in line with previous comparable studies, a planned sample size of 30 participants was selected, with 15 in each group (Ghasemi and Zahediasl, 2012, Falla et al., 2014). This sample size was supported by an *a-priori* power calculation using G*Power 3.1.9.4 (Faul et al., 2007) to estimate the within-between interaction for a repeated measures ANOVA. A sample size of 22 was recommended to identify a small-moderate effect (0.02,) with $\alpha = 0.05$, power = 0.8 for the planned measurement.

3.2.2 – Questionnaires

Prior to testing, sample characteristics including participant age, sex, height and weight (from which BMI was calculated) were collected (Kirk et al., 2009). Additionally, participants from both groups were required to complete several baseline questionnaires to characterise the

sample; including the level of disability, intensity of pain, and current level of activity. The content of these questionnaires broadly reflected PROMs which are most commonly used clinically (Clohesy et al., 2018). As such, the baseline questionnaires included measures of disability, fear surrounding movement, CNSLBP symptoms, and general health and physical activity.

Participants were asked to complete the Oswestry Disability Index (ODI), as it has previously been shown to have good construct validity, and good to excellent reliability (ICC range 0.84-0.94) (Fairbank and Pynsent, 2000, Vianin, 2008). It has also been demonstrated to be more responsive than other disability questionnaires in samples with CNSLBP (Fairbank and Pynsent, 2000, Frost et al., 2008), and was identified as the most commonly used PROM for participants with CNSLBP. The results will be interpreted according to suggested guidelines as follows; 0-20%, – minimal disability, 21-40% – moderate disability, 41-60% – severe disability, 61-80% – crippled, 81-100% – bed-bound or exaggerating (Fairbank and Pynsent, 2000).

The Tampa Scale for Kinesiophobia was used to assess any fear surrounding movement related to pain (Miller et al., 1991). Results from the use of this scale have been shown to demonstrate good test-retest reliability with a statistically significant Pearson's correlation ($r=0.78$).

An 11-point Pain Numeric Rating Scale (0-10) (PNRS) was used to assess current pain at the time of testing, and pain over the prior week. This tool was selected for the ease of use and close correlations of scores to visual analogue scales requiring greater dexterity and precision (Breivik et al., 2008). The ratings were interpreted as follows; 0 – no pain, 1-3 – mild pain, 4-6 – moderate pain and 7-10 – severe pain (Breivik et al., 2008).

Information on the general health of participants at the time of testing was collected using the RAND 36-item health survey. The RAND-36 method is an alternative technique of scoring the SF-36 using open-source algorithms (RANDHealth, 2016). This scoring system has been shown to have good construct validity and high internal consistency as a measure of health (Hays et al., 1993, VanderZee et al., 1996, Moorer et al., 2001). Guidance for this tool indicates that a score of 100 is indicative of the '*highest level of functioning possible'* with progressively decreasing function to zero (Hays et al., 1993, RANDHealth, 2016).

Additionally, it was planned that the International Physical Activity Questionnaire was to be used to gain metrics on the level of physical activity within the participant groups in the week prior to data collection (Craig et al., 2003). This questionnaire has been shown to have good reliability, with a result in a British population of 0.7 on Spearman's reliability coefficient. Unfortunately, in this study, a page was omitted during the printing process which was not noted until several participants had been tested, it was therefore decided to remove this questionnaire and destroy all partial data.

Throughout the endurance task (see below), the rate of perceived exertion (RPE) was recorded at 30 second intervals and immediately following task failure using the Borg RPE scale (Borg, 1998). This measure was used to assess the perceived exertion of the participants throughout the task and to identify if either group showed greater exertion.

3.2.3 – Experimental Task

To complete the endurance task, participants were required to maintain an Ito test, as described by Ito et al. (1996) and Muller et al. (2010) until task failure or until 300s (Fig 3.1).

Participants were first asked to lie prone on a plinth, with a firm semi-circular foam pad (18 cm diameter) centred below the anterior superior iliac spines. To complete the endurance task, participants were asked to lift their sternum from the plinth, raising their upper body by ~15°. While maintaining this position, participants were asked to keep their arms in line with the body axis and not in contact with the plinth; participants were also required to contract their gluteal muscles and retain a neutral neck position. Prior to beginning the task, an investigator demonstrated the correct position for completion of the Ito test, and participants were permitted to complete a short 5s contraction to ensure they had the correct technique.



Fig. 3.1 – Demonstration of the Ito test position

Throughout the task, the angle of the body axis was monitored visually and participants were alerted if their body axis was approaching the upper or lower acceptable limits (±10°) (Demoulin et al., 2007). Task failure was determined by a drop in the angle of trunk of greater than 10° at any point. While completing the contraction, participants were timed using a stopwatch, the time was recorded until task failure or until the maximum contraction duration

was reached (300 s). Throughout the task, participants were given verbal encouragement and at 30s increments were provided with feedback for how long they had sustained the contraction.

3.2.4 – Experimental Set-Up

HDEMG signals were recorded from the lumbar ES using 13x5 semi-disposable 2-D electrode grids (OT Bioelettronica, Italy). Electrodes were spaced evenly with a 1 mm diameter and an 8 mm inter-electrode distance; one corner electrode was missing in each grid to provide directional reference. Electrodes were positioned over the lumbar ES on the right-hand side in control participants and the most painful side in the LBP group. Signals were recorded unilaterally due to hardware limitations (number of channels available). Where equal pain was reported bilaterally, participants were randomly allocated a side (Fig. 3.2).

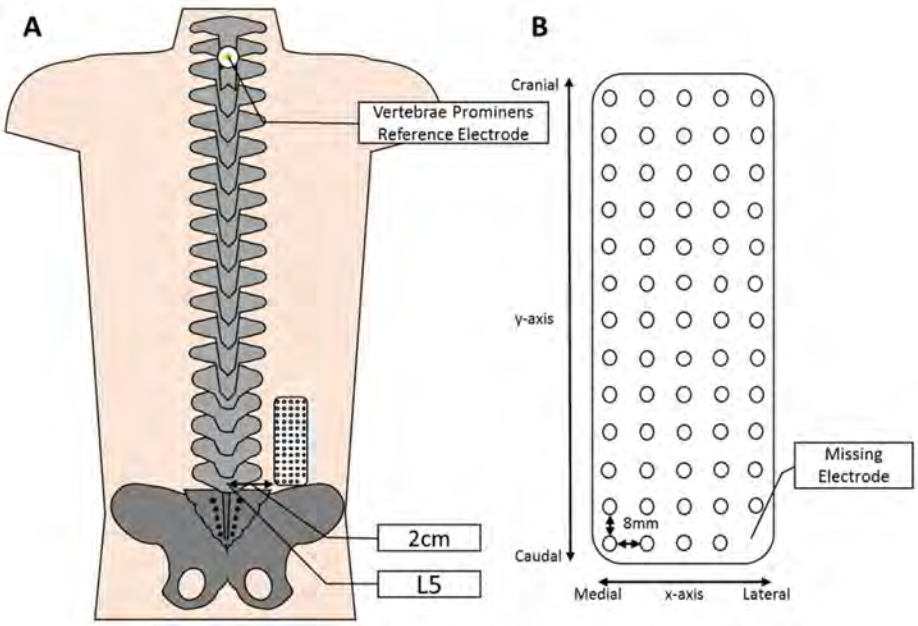


Fig. 3.2 – Showing (A) the positioning of the HDEMG grid on the lumbar ES of the participant and (B) a schematic of the electrode grid showing the x- and y-axes, reference electrode and inter-electrode distance (not to scale).

Prior to the application of electrodes, the skin in the region lateral to the lumbar spine was prepared by firstly shaving the area if needed and then applying an abrasive paste (to remove keratinised skin cells and so reduce the impedance of the electrode-skin contact (Criswell, 2010) (SPES Medica, Italy), and finally washing and drying the region. The electrodes were prepared by applying a thin custom double-sided adhesive foam pad to the electrode grid (SPES Medica, Genova, Italy). The cavities of the electrode grids were then filled with an electroconductive paste to ensure good electrode-skin contact (SPES Medica, Genova, Italy). As there is no way of differentiating different portions of the ES *in vivo*, the electrode was placed on the ES in accordance with adapted bipolar-EMG guidelines and previous studies (Barbero et al., 2012, Falla et al., 2014). Therefore, the grids were applied to the skin approximately 2cm lateral to the lumbar spinous processes, starting at the level of the L5 and extending to approximately the level of L2-L3, as described previously (Falla et al., 2014). Reference electrodes were placed on prepared skin over the right anterior superior iliac spine and on the spinous process of the vertebra prominens (typically C7).

A twin-axis SG150B digital goniometer (Biometrics Ltd., Gwent, UK) was applied to the right mid-axillary line of the participant. Only one axis (sagittal plane) was used for analysis. The lower sensor was attached to the centre of the iliac crest, with the midline of the sensor in line with the greater trochanter of the femur. With the participant positioned in prone on the plinth, the resting angle was calibrated as 0°, with trunk deviation measured from this point. EMG signals and angular data were sampled at 2048Hz and amplified (400-channel EMG amplifier Quattrocento, OT Bioelettronica, Torino, Italy; -3-DB, bandwidth 10-500 Hz)) by a factor of 150 and converted to digital form by a 16-bit analogue-to-digital converter. Collected

signals were stored on a computer hard drive and later analysed using a custom code on MATLAB (The Mathworks Inc., USA).

As described previously by Falla et al. (2014), each grid of electrodes recorded 64 monopolar signals. These signals were then processed offline to form horizontal derivatives across the grids. This was achieved by first filtering the monopolar signals using a 20-350 Hz band-pass filter and then adjacent signals were processed to produce 59 bipolar EMG signals. The amplitude (RMS) and mean spectral power frequency (MNF) for each bipolar derivation were then calculated. The individual RMS and MNF values for each bipolar signal were averaged to produce the mean RMS and MNF values across the grid. The RMS values for each bipolar signal were used to create a topographical map of ES activity. This map was used to determine the location of the x- and y-coordinates of the centroid as described previously (Abboud et al., 2014, Falla et al., 2017, Falla et al., 2014, Farina et al., 2008, Madeleine et al., 2006, Tucker et al., 2009). The location of the centroid was averaged across the 10s or 10% epochs (normalised units of time representing 10% of the total endurance) for further use in analysis.

The values for the x- and y- coordinates of the centroid were analysed as an absolute shift in mm from the start point quantified in the first 10% epoch (Falla et al., 2014). As movement of the centroid was both cranial and caudal in both groups, to allow for comparison between groups of the absolute shift in the y-coordinate of the centroid, both positive and negative movements were made positive.

3.2.5 – Statistical Analysis

Statistical analysis was performed using SPSS 24 (IBM, USA) with an alpha level set at 0.05, all statistical assumptions were met (Field, 2013). Regression analysis and analysis of covariance (ANCOVA) tests were performed using Prism (GraphPad, USA). Where P-values were reported on SPSS as 0.000, they have been stated as $P < 0.001$ herein. Effect sizes have been reported where appropriate with ANOVA results, in the format of η_p^2 values. For interpretation of these values, effect sizes are defined as small ($\eta_p^2 = 0.01$), medium ($\eta_p^2 = 0.06$) or large ($\eta_p^2 = 0.14$) (Lakens, 2013).

3.2.5.1 – Questionnaire Data

The questionnaires used to characterise the sample were interpreted according to their respective guidelines (Childs et al., 2005, Fairbank and Pynsent, 2000, Hays et al., 1993, Miller et al., 1991). Student t-tests were performed for each group to identify differences between the samples at baseline across all questionnaire data.

3.2.5.2 – Endurance

A student t-test was performed in order to identify any differences in endurance times between groups. No direct comparison of the values reported for perceived exertion could be made between groups, as the time to task failure varied between groups. Therefore, the initial value after 30s, the value at the mid-point of endurance, and the level of exertion at task failure were determined for each participant. Significant differences between groups were investigated using a repeated measures ANOVA.

3.2.5.2 – HDEMG

In order to make comparisons between groups with different times to task failure, the total contraction time for each participant was normalised into 10% epochs of the total endurance time (Farina et al., 2008). Repeated measures ANOVAs, with factors of group (CON and LBP) and time (10 epochs) were used to compare differences in EMG variables between groups. Newman-Keuls post-hoc tests were also conducted where appropriate.

To test H3.1 and H3.2 and identify trends in the displacement of the y-coordinate of the centroid between groups, a linear regression was performed. To ensure that the results were not affected by the normalisation of time, this regression was performed using absolute endurance times and y-coordinate displacement values calculated from the position of the centroid in the first 10s epoch. The regression lines for the CON and CNSLBP groups were compared for statistical significance using an ANCOVA.

Finally, in order to assess myoelectric manifestations of muscle fatigue, linear regressions were performed on RMS and MNF variables (Lariviere et al., 2002a). For each participant, the relationships between RMS and time to task failure, and MNF and time to task failure were computed. In this analysis both absolute values for RMS and MNF across time, and normalised values (using the first 10s epoch as a reference) were considered and the resulting slopes extracted. Independent samples t-tests were then performed on the slopes for each condition to identify the mean slope for each group and identify any differences between these means (Page and Descarreaux, 2012, Roy et al., 1995).

3.3 – Results

3.3.1 – Participants

Complete data sets from 13 LBP and 13 CON participants were collected, data from four additional participants (2 LBP/2 CON) was excluded due to presence of artifacts/noise in the recordings. The included population characteristics are reported in Table 3.1. No significant anthropometric differences were found between groups for height or weight and the BMI for both groups was within the 'normal weight' range (Stenholm et al., 2017). However, as anticipated, the LBP group presented with higher levels of disability (ODI -13.16%, mild disability) and lower general and emotional health (RAND 36 item health survey). Prior to data collection, the LBP group reported a current pain level of 1.92 out of 10, but a usual pain of 2.92, characterising the pain within the group as mild severity (Breivik et al., 2008).

Characteristic		LBP n=13	Control n=13	P-Value
Age (Years)		27.39 ±9.7	26.46 ±5.0	-
Sex (# Males)		6	7	-
BMI		24.78	23.78	-
ODI (%) *		13.16% ±8%	0.00%	< 0.001
TSK		25.31 ±4.89	22.31 ±7.20	-
PNRS	**Current Pain ***	1.92 ±1.44	0	< 0.001
	Usual Pain *	2.92 ±1.98	0	< 0.001
RAND 36 Item Health Survey	**Physical Functioning ***	82.52 ±10.64	99.30 ±2.52	< 0.001
	Emotional Wellbeing *	69.85 ±17.33	82.46 ±7.58	0.024
	Pain *	68.46 ±16.79	95.00 ±8.6	< 0.001
	General Health *	64.62 ±20.15	82.31 ±10.53	0.010

Table 3.1 – Mean participant characteristics separated by group, showing the standard deviation where appropriate. Where significant differences occur, the characteristic is marked with an asterisk and a P-value is displayed.

3.3.2 – Endurance

Statistically significantly lower endurance times were recorded for the LBP group ($F = 8.4$, $P < 0.001$) compared to the control group (186.3 ±72.3s and 283.0 ±33.0s respectively). With 96.7s difference, this equates to the LBP group maintaining the contraction for 65.8% of the total time for the CON group on average. It is possible that this measure underestimates the difference in endurance time, as 10/13 CON participants were stopped at 300s, in contrast to 2/13 LBP participants. The mean values for initial, middle and final perceived exertion are shown in Fig. 3.3. No significant differences were found between groups for exertion at any point ($F = 1.42$, $P = 0.216$).

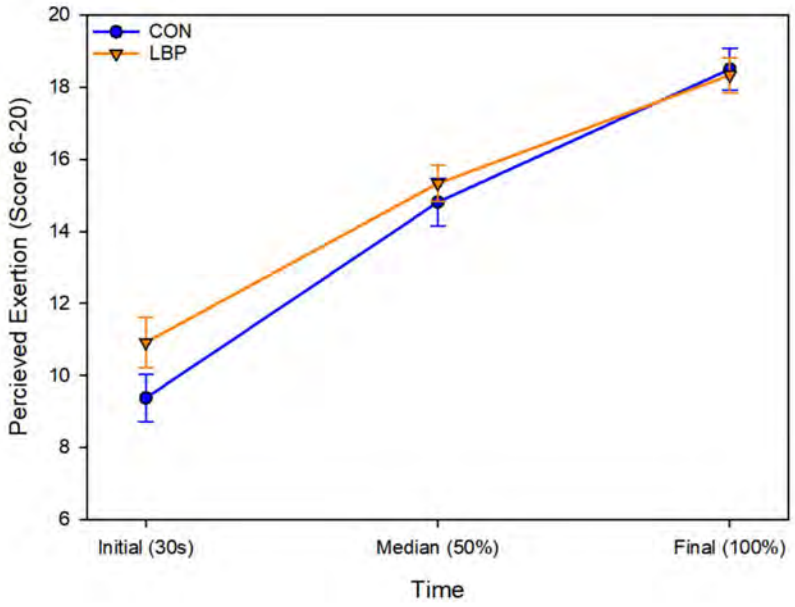


Fig. 3.3 – The mean values for the initial, mid-point and final values (and SE) for the RPE as reported by participants during the endurance task. No significant differences were found between groups for exertion during the task.

3.3.3 – Muscle Activity

3.3.3.1 – HDEMG amplitude and mean frequency

Across the duration of the contraction, there was no significant difference in normalised RMS between groups. However, when reviewing the topographical maps of the EMG amplitude, the RMS appeared to be less evenly distributed in those with LBP (Fig. 3.4). On average, CON participants showed a larger distribution of the activity throughout the ES, whereas LBP participants showed less diffused activation which tended to be more cranial. When quantified, an even distribution across the entire grid was observed in 11 CON and four LBP participants. Distribution was weighted cranially in one CON and eight LBP participants and distribution was focussed in the middle of the grid for one CON and one LBP participant (Fig 3.5).

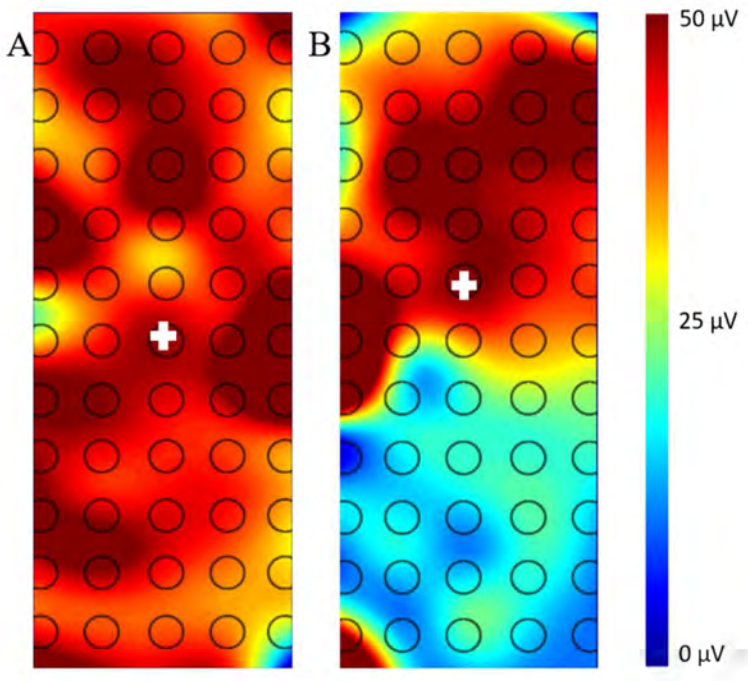


Fig. 3.4 – Representative RMS topographical maps for CON (A) and LBP (B) participants during the endurance task. The centroid is depicted by the crosshair and the scale is indicated in µV.

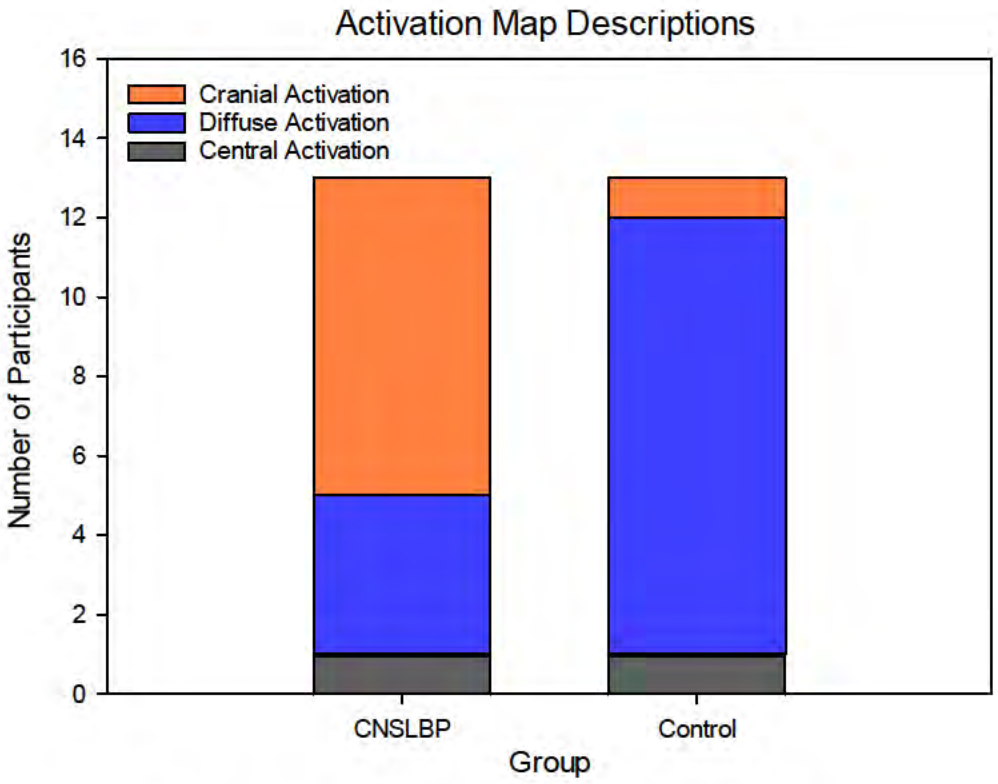


Fig 3.5 – The classification of the distribution of activity in RMS maps

There were no statistically significant differences between groups for the change in RMS throughout the task ($F = 1.42$, $P = 0.216$). There were also no statistically significant increases or decreases in the mean RMS recorded for either group at any point during the endurance task ($F = 0.929$, $P = 0.344$). No statistically significant differences between groups were observed for the mean MNF at any point during the contraction ($F = 1.118$, $P = 0.334$).

3.3.3.2 – Centroid of the EMG RMS map

No significant differences were found between groups for the position of the x-coordinate of the centroid (medial-lateral direction) throughout the task (initial position – $F = 2.27$, $P = 0.77$; shift over the duration of the contraction – $F = 2.27$, $P = 0.77$).

The y-coordinate of the centroid (cranial-caudal direction) in CON participants was found to be systematically more caudal than the LBP group (main effect for group; $F = 44.00$, $P < 0.001$, $\eta_p^2 = 0.65$). The y-coordinate in CON participants was found to be approximately 42.0 mm (± 4.99 mm) cranial of the reference electrode, whereas for the LBP group, the y-coordinate was approximately 53.6 mm (± 3.64 mm) cranial of the reference electrode. Throughout the endurance task there was a mean difference between the LBP and CON in the y-coordinate position of 11.6mm (Fig. 3.6).

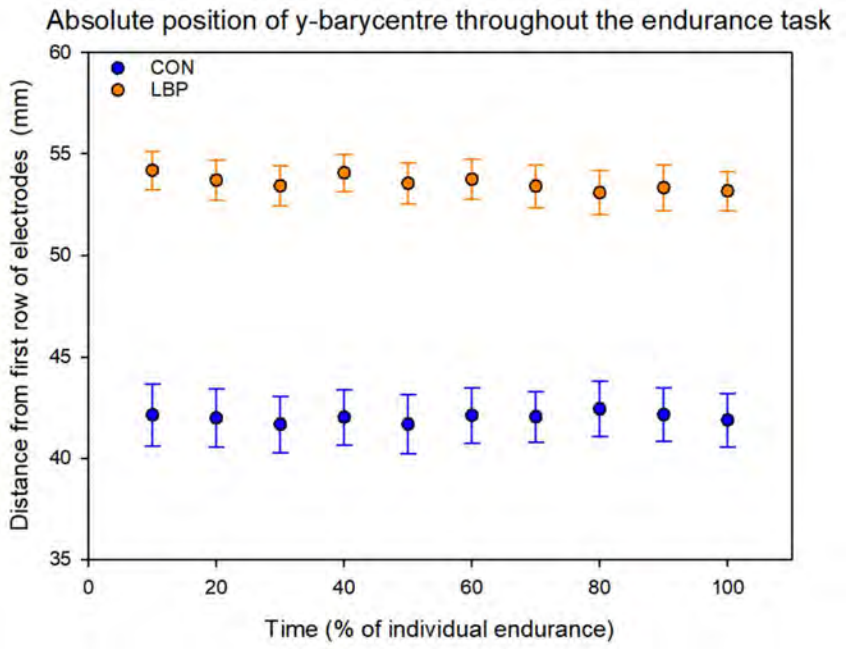


Fig. 3.6 – Absolute mean locations (and SE) of the y-coordinate of the centroid for CON and LBP group throughout the endurance contraction

Using the location of the y-coordinate of the centroid in the 1st epoch as a reference point, the displacement was calculated for each 10% epoch. To achieve this, the shift in mm was measured from the position of the y-coordinate in the first epoch, this could be either a positive (cranial movement) or negative (caudal) value. No clear direction of shift was found (cranially or caudally) as groups showed both cranial and caudal movements (CON – six cranial, seven caudal; LBP – nine cranial, four caudal). To better understand the movement of the centroid, all values for displacement were therefore made positive and so net displacement was used for all y–coordinate shift results. At task failure, the mean y-coordinate displacement for the CON group was 2.10±0.45mm whereas for the LBP group it was 1.40±0.29mm. Both groups showed a significant displacement of the centroid in the y-axis over time ($F = 10.32$, $P=0.004$, $\eta_p^2=0.30$) and a significant displacement within each group ($F = 9.9$, $P=0.01$) (Fig. 3.7). There was no interaction between groups for the displacement of the y-coordinate in the data which had been normalised to task failure ($F = 1.709$, $P = 0.134$).

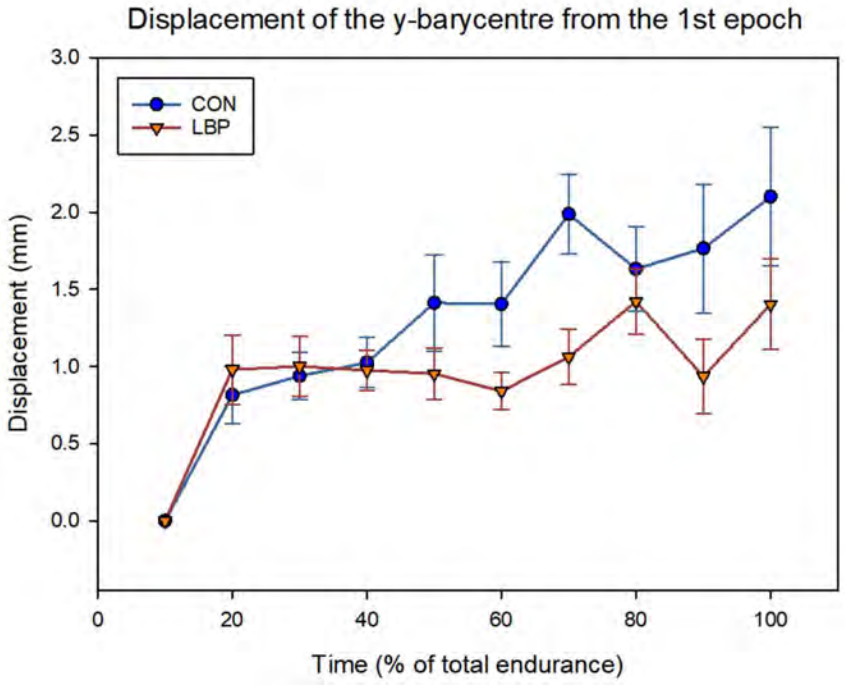


Fig. 3.7 – Displacement of the y-coordinate of the centroid from the position in the first 10% epoch (and SE), showing a significant displacement of the y-coordinate for both the CON and LBP group.

The regression analysis performed using absolute values for time showed a significant relationship between the shift in the y-coordinate of the centroid and the time to task failure (Fig. 3.8) for both groups (CON – r^2 = 0.142, P < 0.0001; LBP – r^2 = 0.053, P = 0.0004). Additionally, ANCOVA analysis showed that there was a significant difference between the regression lines for each group (P=0.0183) indicating that the relationship between y-coordinate shift and time was significantly different between groups (LBP/CON) (Zar, 2010).

Myoelectric manifestations of muscle fatigue showed no differences under any condition. There were no differences in the slopes between groups for absolute RMS (P = 0.71), normalised RMS (P = 0.37), absolute MNF (P = 0.48) or normalised MNF (P = 0.79).

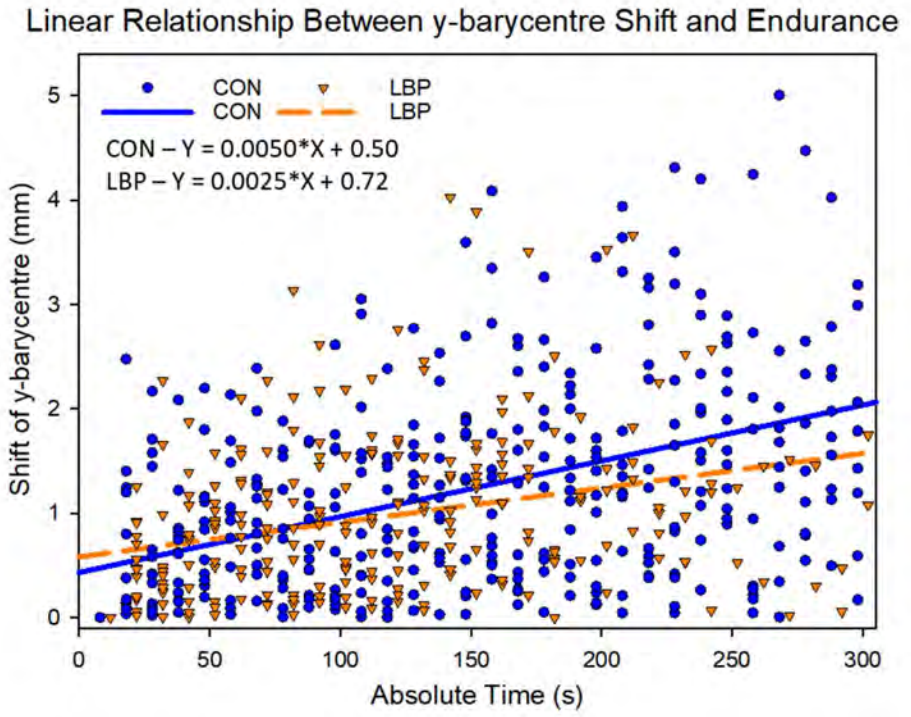


Fig. 3.8 – Linear regression analysis on the shift in y-coordinate of the centroid , showing significant variation in the shift of the y-coordinate over the length of the endurance contraction (P=0.0183). Two CON points where shift was more than 6mm not shown.

3.4 – Discussion

This is the first study to assess muscle activation behaviour using HDEMG during a functional position-matching lumbar endurance task in people with and without CNSLBP. Findings revealed an altered motor control strategy to a standardised endurance task in people with mild to moderate CNSLBP, with evidence of activation of more cranial regions of the lumbar ES compared to pain-free individuals. Moreover, a relationship was also demonstrated between the extent of redistribution of muscle activity and endurance time which has important implications for the understanding of the neurophysiological responses to fatigue.

3.4.1 – Distribution of Activity

Throughout the task the y-coordinate of the centroid for the CON group was 12mm caudal to that of the LBP group. Previous studies which have induced pain via injection of hypertonic saline, have shown that areas with greater pain show reduced activity and that in an acute painful condition, the muscle activation can shift outside of the painful region (Falla et al., 2017, Falla and Farina, 2008a, Madeleine et al., 2006). Although somewhat speculative, it is likely that a more caudal centre of contraction could indicate a more biomechanically favourable contraction through activating a greater number of fibres. In this instance, those with pain appear to have shifted the activity in the ES more cranially. A more caudal contraction, which is distributed over a larger area of the muscle would be able to utilise the larger volume of muscles from lower lumbar vertebrae and spread the load more effectively across a greater number of muscle fibres creating a longer lever arm (Bogduk, 2005). The longer lever arm would act to minimise the force needed to sustain the contraction and the diffuse activation would reduce localised fatigue, facilitating sustained endurance.

3.4.2 – Redistribution of lumbar ES activity

During the Ito test, the CON participants showed a greater shift of the centroid of the EMG amplitude map indicating a greater redistribution of lumbar ES activity than the CNSLBP group. It was also shown that the amount of redistribution increased progressively over the duration of the task and that there was an association between the extent of redistribution of activity and endurance time. As previously described by Falla et al. (2014), a redistribution of activity likely prevents localised muscle fatigue through the build-up of metabolic factors and overload on specific regions of the muscle. The task used in Falla et al (2014) was dynamic and consisted of periodic contractions, whereas the contraction used here is static and so the tissue would be under further strain due to decreased blood flow and ischemia (Masuda et al., 1999).

The results of this study do not support a direction of shift for this task as there was no clear preference for a direction in either group. However, this study differs from previous studies, which used HDEMG to examine the lumbar muscles as it does not involve an external force. Gallina et al. (2013) investigated the significance of the shift in the *trapezius* muscle and determined that the direction of shift was task dependant. Russ et al. (2018) and Thomas et al. (2011) showed that there were specific differences in lumbar endurance between force- and position-matching tasks, the reasons for which they were unable to describe. The lack of a clear direction of shift seen in this study, may imply a focus of muscle activity in a more biomechanically favourable point for each participant. As there was no specific point to 'push' against, the centre of activity for each participant was likely determined by individual anthropomorphic features, for example a greater trunk length to leg length ratio. In this study, it is speculated that as participants were not secured to the plinth or pushing against a point, the

impact of the relative size and weight of the legs compared to the upper body would impact on the stability of the participant while contracting. Thus, the participant might be likely to sustain a contraction which affords them the optimal stability for their individual anthropomorphic characteristics.

3.4.3 – Muscular Activity

Biomechanical and anatomical models of the lumbar musculature indicate that the shared insertions of portions of the ES cause a diagonal slight overlapping of successive superficial fibres (Bogduk, 2005, Bogduk, 1980). According to anatomical studies, the portions of the ES which are likely to be muscular in the region beginning 2cm lateral to L5 include the *iliocostalis lumborum pars lumborum* and the *iliocostalis lumborum pars thoracis*, with the muscular portions of the longissimus being too medial or too cranial to be covered by the electrode grid. In the *pars lumborum*, most deep and lateral fibres are from L5, the most superficial and medial fibres are from L1; each successive lamina of fibres slightly overlaps the previous layer (Bogduk, 2005, Christophy et al., 2012). The Ito test used in this study is designed to gain relative isolation of the lumbar musculature, so the distribution and redistribution of activity in this portion of the muscle is thought to be key to understanding endurance in this task (Muller et al., 2010). It is therefore suspected and proposed that due to pain in the lumbar region, participants with CNSLBP utilised a motor control strategy which preferentially activated different portions of the muscle, such as the more cranial *iliocostais lumborum pars thoracis* and thus led to a shorter time to task failure than the CON group. As no imaging was used in this study, the exact distribution of activity among portions of the ES,

and what effect any individual variations in muscle architecture or fibre distribution could have on the activation pattern remains unknown (Mannion et al., 1997, Mannion et al., 2000).

3.4.4 – Endurance and Fatigue

The LBP group demonstrated endurance which fell significantly short of the CON group. Similar findings have been demonstrated in previous studies investigating lumbar endurance to task failure, however the absolute endurance times reported here were significantly higher than those reported following a Sørenson test (Abboud et al., 2014, Jubany et al., 2017b). This difference could be attributed in part to the differences between force-matching tasks previously used, and position-matching such as the Ito test used here (Russ et al., 2018). However, Muller et al. (2010) reported lower endurance times for a position-matching Sørenson test when compared directly with an Ito test. In this instance it may also be relevant to consider the biomechanical and myoelectrical differences between the Ito and Sørenson positions. As discussed previously, muscle activation in the Ito test is focussed on the lumbar region while the Sørenson has shared activation between the lumbar and hip extensors, possibly contributing to differences in endurance time (Muller et al., 2010). Additionally though both tasks are measures of lumbar endurance, each requires a different position to be held; with the Ito test requiring spinal extension to be sustained and the Sørenson requiring an unsupported neutral spine maintained against gravity (Muller et al., 2010). Due to this, it is likely that the point at which the participant's centre of mass is supported may be lower in the Ito test, producing a lower moment.

At task failure, both LBP and CON participants reported a mean RPE of between 18.3 – 18.5, indicating that both groups reached a similar level of exertion. Analysis of the MNF

results and the indices measuring the myoelectric manifestations of fatigue revealed that there were no significant differences between the CON and LBP groups. Previous HDEMG studies evaluating fatigue of the lumbar ES have shown greater myoelectric manifestations of fatigue than these results suggest, however other studies also did not find significant differences between groups (Abboud et al., 2014, Tucker et al., 2009). This could be somewhat explained by recent studies which have demonstrated that frequency variables, including MNF, do not accurately predict motor unit recruitment during contractions (Merletti and Farina, 2016, Del Vecchio et al., 2017). Additionally, it has been shown in the knee extensors that myoelectric manifestations of fatigue are only seen when the exertion exceeds 40% of the MVC (de Ruiter et al., 2012). Two exercises in a study by Plamondon et al. (2002) were similar in position and function to the Ito test, these exercises were found to be between 26-32% of a participant's MVC. As the current study did not assess the functional capacity of the participants, the results for MNF may be affected by the task being below 40% of an MVC for some participants.

The results of this study coalesce to indicate that people with mild to moderate CNSLBP utilise a different motor control strategy to complete the task. This strategy was characterised by a reduced activation of the ES, which was focussed more cranially and throughout the task showed less redistribution of activity. It appears that participants used less favourable portions of the ES to complete the task, which lead to shorter endurance times.

3.4.5 – Reliability

As discussed in the section 1.4.4, the reliability of using HDEMG in the lumbar region of individuals with CNSLBP has not been specifically investigated previously, even though the reliability of bipolar surface EMG measures have been demonstrated in other regions (Brandt et al., 2017, Schinkel-Ivy et al., 2015) and the reliability of tracking individual motor units over

time from HDEMG has been confirmed (Martinez-Valdes et al., 2017). In this study, while effect sizes are considered large and the sample size was sufficient, the question of reliability limits the clinical relevance (Cohen, 1988, Lakens, 2013). Since the reliability of HDEMG recordings from the lumbar ES as not been established in this population, the strength of the results remains doubtful. As such, if the results were to be interpreted in line with the GRADE criteria described in Chapter 2, the potential inconsistencies in the technique would reduce the overall confidence in the strength of the results (Guyatt et al., 2011c, Guyatt et al., 2008).

3.4.6 – Strengths and Limitations

A strength of this study was its use of HDEMG to present a more comprehensive characterisation of ES activity during an endurance test, a test which can be easily replicated in a clinical environment. In addition, the Ito test presented here has previously been found to better isolate the lumbar musculature than the Sørenson test (Muller et al., 2010). As no significant differences were found in the RPE between groups, it is supported that the Ito test was a suitable test for this population. The selection of ±10º in trunk angle to mark task failure was selected for this study in line with previous work. However, these previous studies used visual changes or manual goniometers to assess trunk angle, and the digital goniometer used here could have allowed a more accurate approach (e.g., ±5º). However, as no clear guidelines for task failure have been validated for the Ito test or for the placement of the digital goniometer to measure this angle, the task failure criteria of ±10º was considered an appropriate option. Nonetheless, the large variation in trunk angle that a total of 20º affords from the starting position could be perceived to affect the redistribution of activity during the task. However, as systematic differences were seen between groups for all values related to the RMS, it is thought that the differences between groups are valid, but could hinder comparison to other lumbar

endurance tasks. This study overcomes limitations identified in the studies reviewed in Chapter two as it was reported in line with the STROBE guidelines, and so it is expected that assessment with the modified NOS scale described in Chapter two, would identify a low risk of bias within the methods and reporting of this study.

The CNSLBP group presented with mild levels of pain and mild disability (Breivik et al., 2008, Fairbank and Pynsent, 2000). The sample size was relatively small and the participants with CNSLBP presented with relatively mild symptoms, significant group differences were revealed. This result may not be generalisable to individuals with greater pain severity or disability, however the effect that more severe symptoms may have on muscle activity is not fully known so this remains speculative (Arendt-Nielsen and Graven-Nielsen, 2008, Mannion et al., 2000). Similarly, the task used here was static in nature, and so may not be reflective of functional movements used in tasks of daily life. Activity was only recorded unilaterally and as such does not fully represent a measure of the bilateral activation required to complete the task. As a more painful side was selected by participants, it is possible that activity may have differed between sides.

3.5 – Conclusions

The findings from this study suggest that people with low levels of disability and mild CNSLBP symptoms display less spatial redistribution of lumbar ES activity during an endurance task than an age and gender matched pain-free control group. Moreover, people with CNSLBP were found to engage more cranial regions of the lumbar ES during trunk extension; likely reflecting an inefficient motor strategy. However, the generalisation of this result is limited due to the specific lumbar focus of electrode placement and the static nature of the task. As such, in order to fully understand how the distribution of muscle activity is affected by

CNSLBP, further research is required. Additional studies which use HDEMG to investigate the spatial distribution of muscle activity across the whole lumbar region during dynamic tasks are required to understand the implications for functional activities of daily life.

CHAPTER 4

PEOPLE WITH LOW BACK PAIN DISPLAY A DIFFERENT DISTRIBUTION OF ERECTOR SPINAE ACTIVITY DURING A SINGULAR MONO-PLANAR LIFTING TASK: A CROSS-SECTIONAL STUDY

This Chapter reports in full a manuscript which has been published previously (Sanderson et al., 2019a). Changes have been made in the text of this Chapter for the purposes of a thesis, specifically;

- The introduction has been edited to reflect the content of previous Chapters in this thesis and avoid repetition
- Where overlapping occurs, areas of the methodology have been reduced to reflect the previous elaborations in Chapter three
- The discussion and conclusion have been edited to increase cohesion between linked studies in later Chapters.

However, the majority of the text in this Chapter reflects the published manuscript verbatim and has been reprinted with permission from Frontiers.

Publications and Presentations

1. **Sanderson, A.,** Cescon, C., Heneghan, N. R., Kuithan, P., Martinez-Valdes, E., Rushton, A., Barbero, M., Falla, D. 2019. People with Low Back Pain Display a Different Distribution of Erector Spinae Activity During a Singular Mono-Planar Lifting Task. *Frontiers in Sports and Active Living*, 1. **(Appendix 1)**

2. **Sanderson, A.,** Cescon, C., Kuithan, P., Rushton, A., Heneghan, N.R., Barbero, M., Falla, D. Spatial distribution of erector spinae activity in people with low back pain during a dynamic lifting task. 19th Congress of International Federation of the Associations of Anatomists. London, UK, 9th – 11th August 2019.

3. **Sanderson, A.,** Cescon, C., Kuithan, P., Rushton, A., Heneghan, N.R., Martinez-Valdes, E., Barbero, M., Falla, D. People with chronic low back pain display an altered distribution of erector spinae activity during a singular mono-planar lifting task. XXIII Congress of the International Society of Electrophysiology and Kinesiology (ISEK). Virtual Congress. July 12-14, 2020. (Accepted)

4 – Abstract

While the results of the review in Chapter two identified few consistent differences in the magnitude of muscle activity, Chapter three demonstrated clear differences in the spatial distribution of ES activity. This cross-sectional study aimed to investigate variation in muscle activity in the lumbar and thoracolumbar region during a dynamic singular mono-planar lifting task in people with CNSLBP. Activity from the lumbar and thoracolumbar ES of 14 CON (27.36 ±11.4 years) and 11 LBP participants (32.45 ±16.3 years) with mild CNSLBP (2.59 ±1.64/10) was recorded using four HDEMG grids. In the task, participants lifted a 5kg box from knee height to sternal height, and then returned the box to the starting position. The RMS of the HDMEG signals were used to create topographical maps of the distribution of muscle activity. Kinematic data were recorded, focusing on the 3-D relationship between lumbar and thoracic movements. The centre of muscle activity for CNSLBP group was found to be systematically more cranial throughout the task compared to the control participants ($P<0.05$). Participants with CNSLBP also had lower signal entropy ($P<0.05$) and lower absolute root mean squared values ($P<0.05$). However, there were no differences between groups in kinematic variables, with no difference in contributions between lumbar and thoracic motion segments ($P>0.05$). These findings suggest that participants with CNSLBP continue to utilise an altered motor control strategy during a dynamic task. While there were no differences identified in the movement strategy, participants with CNSLBP utilised a less homogenous, less diffuse and more cranially focussed contraction of their erector spinae to complete the lifting movement.

4.1 – Introduction

As considered in Chapter one, in some instances, the prevalence and persistence of CNSLBP is believed to be in part driven by exposure to manual handling, for instance lifting heavy weights in occupational tasks, or assisting moving patients in healthcare professions (Silvetti et al., 2019, Andersen et al., 2017, Wai et al., 2010). Most studies which have investigated lifting in people with CNSLBP have focused on repeated lifting movements, and while this is reflective of some occupational tasks (*e.g.* factory work), there are occupations which involve less frequent lifting which may still be relevant for the initiation and/or perpetuation of CNSLBP (*e.g.* retail). For example, several studies have investigated links between manual handling and low back pain in nurses (Byrns et al., 2004, Stobbe et al., 1988), and while it is acknowledged that this is not a primary role of a nurse, the evidence suggests a link between this occasional lifting and CNSLBP.

The review in Chapter two identified no consistent differences in the magnitude of muscle activity between participants with and without CNSLBP. This result was consistent for lifting tasks, which were considered within the review, with two studies identifying no differences in activity and one indicating greater activity in CNSLBP. However, as discussed within the review, it is important to note that two of these studies identified differences in the topographical distribution of activity in participants with CNSLBP, indicating that this is an area which warrants further investigation (Falla et al., 2014, Lariviere et al., 2002b).

In a study which used HDEMG to investigate the spatial distribution of ES activity during a repetitive mono-planar lifting task (Falla et al., 2014), participants with CNSLBP were seen to have reduced variation in the location of the centroid of the EMG amplitude map, indicating less re-distribution of muscle activity during this task. Although the study revealed

an altered distribution of lumbar ES activity in those with CNSLBP, the findings were limited to the specific region evaluated (i.e. lumbar ES unilaterally spanning a region from approximately L2 to L5). Findings were also potentially influenced by fatigue since the task was performed repetitively (25 cycles, ~200 seconds). In this study, participants with CNSLBP were found to be less able to counter localised fatigue and redistribute activity to regions of the muscle that were not previously as active, instead repeatedly activating more cranial portions of the investigated region. It is possible that the cranial distribution and shift in activity identified in the CNSLBP group could be due to the engagement of the thoracolumbar regions of the ES, which were not investigated. A similar activation of the cranial regions of the ES was identified in Chapter three during a static endurance task (Sanderson et al., 2019b). Several previous studies have investigated dissociation between lumbar and thoracolumbar contributions to movements in CNSLBP populations (Elgueta-Cancino et al., 2014, Langevin et al., 2011), however the relative muscular contributions of these regions has not previously been investigated.

Thus, this study utilises a comprehensive mapping of both lumbar and thoracolumbar muscle activity during a single repetition of a mono-planar lifting task in order to specifically examine the influence of CNSLBP in the absence of a fatiguing task.

4.1.1 – Objectives

The objective of this study was to investigate the spatial distribution, and redistribution, of bilateral lumbar and thoracolumbar ES activity in people with CNSLBP and pain-free controls during a singular monoplanar lifting task; and moreover, any differences in movement strategy in the sagittal plane.

4.1.2 – Hypotheses

H4.1 - It was hypothesised that people with CNSLBP would display a different distribution of ES activity during the lifting task, characterised by a more cranial distribution of activity, centred towards the thoracolumbar region.

H4.2 - Additionally, it was hypothesised that this difference in muscle behaviour would be reflected in a different movement strategy characterised by less lumbar spinal motion in those with CNSLBP.

4.2 – Methods

This study was also classified as an observational cross-sectional study, and is reported in line with the STROBE statement. Data collection was conducted at a laboratory within CPR Spine, University of Birmingham. Recruitment and data collection for this study was completed between June 2017 and March 2018 and data was collected within one session for each participant. Ethical approval for this study was granted by the University of Birmingham Ethics Committee (ERN_16-1389B, Appendix 9). Participants gave written informed consent prior to data collection and all procedures were completed in accordance with the Declaration of Helsinki.

4.2.1 – Participants

Participants aged 18-65 were recruited in the same manner as described in Chapter three. Due to the less fatiguing nature of this task, the upper age limit for this study was raised by ten years to include all adults of working age. Except for the age of participants, inclusion and exclusion criteria for LBP and CON participants in this study mirrored those described in Chapter three. An *a-priori* sample size calculation was completed as described in Chapter 3 with the same minimum sample of 22 identified. The effect size was maintained at 0.2 as this was below the smallest effect identified in Chapter three of $\eta_p^2 = 0.3$.

4.2.2 – Questionnaires

As in Chapter three, prior to commencing data collection, participants were asked to complete several questionnaires in order to assess their baseline characteristics. Similar

questionnaires were used for this study to those described in Chapter three, including the PNRS, IPAQ and the ODI, however some changes were made as detailed below.

In order to streamline the collection of information regarding the participant (age, height, weight and sex) and CNSLBP characteristics, (*e.g.* duration and severity of symptoms) a bespoke back pain questionnaire was created. This questionnaire removed the need for an examiner to note down participant responses to these questions, and ensured these responses could be found in a consistent location (Appendix 10).

The RAND-36 was replaced by the SF-36 (V2). The RAND technique was an alternative version of scoring the SF-36 (V1), with the use of the second version of this questionnaire, the scoring is completed with proprietary software (Optum, Eden Prairie, MN, USA) (Walsh et al., 2003). The SF-36 (V2) has been shown to be a suitable measure of physical and mental health with good internal consistency (Cronbach's alpha 0.8-0.95) and significant construct validity (Jenkinson et al., 1999).

In order to assess any fear surrounding movement or relating to their level of pain, the participants were asked to complete the Fear Avoidance Beliefs Questionnaire (FABQ). This differs from the tool used in Chapter one for pragmatic reasons, as the ethical application which formed the basis for this study was an amendment of a previously accepted application. Thus, the choice was made to not alter the questionnaire previously chosen, as both tools have been demonstrated to have similar excellent reliability in people with CNSLBP (ICC 0.90-0.96) (George et al., 2010).

The Pain Catastrophising Scale (PCS) (Waddell et al., 1993, Osman et al., 1997). The Depression, Anxiety and Stress Scale (DASS-21) were introduced to identify the levels of mental health within the groups (Henry and Crawford, 2005, Lovibond and Lovibond, 1995).

The PCS has been shown to have clinically acceptable reliability (ICC – 0.93, 95% CI – 0.88–0.96) (George et al., 2010), and the DASS-21 showed high reliability correlations (Cronbach's alpha 0.89-0.97) (Crawford and Henry, 2003).

4.2.3 – Experimental Task

The experimental task consisted of lifting a 5kg weighted box between two shelves situated anterior to the participant, simulating an occupational lifting task (Falla et al., 2014). To ensure the correct adjustment of shelf height and distance from the subject, several anatomical features were identified by palpation and measured on each participant. The lower shelf (S1) was set at the height of the lateral femoral epicondyle, the upper (S2) at the height of the manubriosternal junction. Measured from the midpoint of the feet, the shelving was placed the distance from the acromion to the ulna head anterior to the participant (Fig. 4.1).

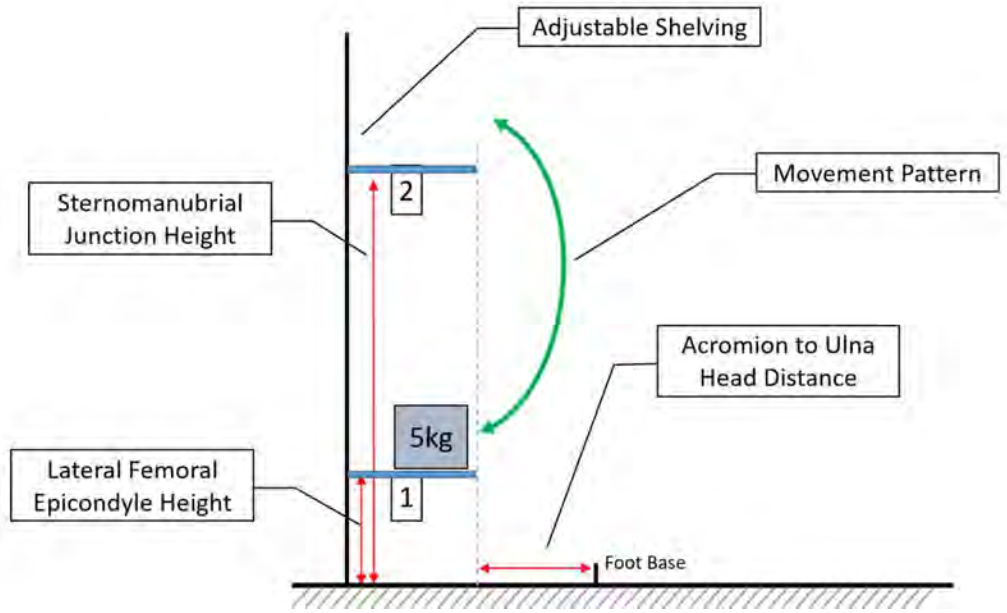


Fig. 4.1 – Depicting the experimental set-up, with adjustable height shelving and the anthropomorphic characteristics which determine height and placement. Foot base describes the midpoint of the feet and the arrow indicates the movements between shelf one and shelf two (not to scale).

To complete the task, participants were required to stand in a quiet standing position, with their heels 17cm apart and feet at a 14° angle to each other (McIlroy and Maki, 1997). During the task, participants lifted the 5kg box (35.5 cm x 29 cm x 13.5 cm) between the shelves starting at the lower shelf. The speed of the task was controlled by a metronome with 2s allocated to each movement between shelves followed by a rest of 2s.

The task was standardised by using a universal weight of 5kg for all participants, which was intended to represent a task of daily life (e.g., lifting shopping) which would not be normalised for each participant. Identical instructions on how to complete the task were provided to each participant, including instructions to prevent the movement of the feet and limit movement at the knee. These instructions were followed by a demonstration of the movement by a researcher, after which each participant was allowed to practice one timed movement with an unweighted box. Following familiarisation with the task, the subjects completed a single cycle of lifting and lowering of the box.

This task was piloted extensively prior to the commencement of data collection to ensure that participants could complete the movement. In response to pilot feedback, the upper shelf was lowered from shoulder height to manubriosternal height, and the speed of the task was reduced from 1s per movement to 2s per movement. To ensure that these alterations had the desired effect, low back pain symptoms were monitored closely by a qualified physiotherapist.

4.2.4 – Experimental Set-Up

4.2.4.1 – Electromyography

Surface HDEMG signals were recorded using four semi-disposable 13x5 2-D electrode grids (OT Bioelettronica, Torino, Italy). Each electrode grid comprised of 64 electrodes spaced evenly with an 8mm inter-electrode distance (Fig. 4.2). The electrodes were adhered to the skin bilaterally, beginning at the level of the L5 spinous process and extending to approximately the level of T8-T10 depending on the height of the participant.

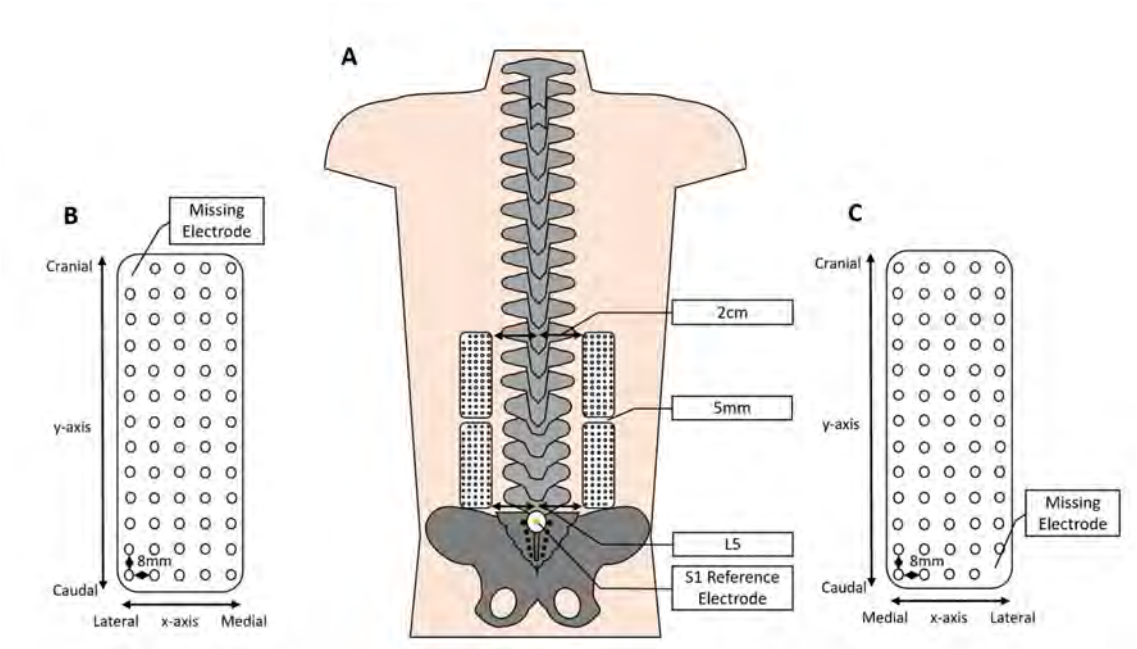


Fig. 4.2 – Depicting (A) the approximate positioning of the HDEMG grids over the lumbar and thoracolumbar ES, 2cm lateral to the spinous processes and spaced 5mm between grids; (B,C) a schematic of the HDEMG electrode grid depicting the inter-electrode distance, the positioning of the x- and y- axes and showing the location of the missing electrode (not to scale).

The electrode grids and the skin in the region that the girds were affixed to were prepared in the same manner as described in Chapter three. In line with previous studies, and

Chapter three, the lower grids were attached 5cm lateral to the lumbar spinous processes, beginning at the level of L5 (Falla et al., 2014, Sanderson et al., 2019b, Martinez-Valdes et al., 2019). The upper grids remained 2cm lateral to the spinous processes; however, the inferior border was affixed to the skin 5mm cranial to the superior border of the lower grid (Fig. 4.2). Reference electrodes were placed on prepared skin overlying the S1 spinous process and the right medial malleolus.

EMG signals were sampled and processed using the technique described in Chapter three and monopolar signals were used for the following analysis. In order to best evaluate the distribution of muscle activity across this larger region in this study, the upper and lower grids combined at the intersection to create large left and right grids.

For each movement phase (S1-2 and S2-1), signals were divided into two equal epochs. The RMS was calculated for each signal and epoch, and these values were used to create topographical maps of the muscle activity. As described previously, the location of the centroid in the x- and y- axes was calculated from these topographical maps (Falla et al., 2017, Tucker et al., 2009, Sanderson et al., 2019b). Additionally, values for the entropy of the signals were calculated for each epoch, with a reduction in this value indicating a more heterogenous contraction (Martinez-Valdes et al., 2019). The RMS and entropy were averaged across the large grids to obtain one value for each side.

4.2.4.2 – Motion Analysis

Three-dimensional kinematic data were recorded using an 8-camera stereo-photogrammetric array (Smart DX, BTS Bioengineering, Milan, Italy). Retroreflective markers

were adhered on the participant's skin overlying anatomical landmarks, which were identified by palpation. The landmarks chosen for this task included unilateral points on the spinous processes of C7, T6, T12 and S1; and bilaterally over the remaining landmarks; 10cm lateral to the spinous processes of T6 and T12; the iliac crest on the mid-axillary line; the lateral femoral epicondyle; the lateral malleolus, the head of the fifth metatarsal and the calcaneal tuberosity. The pattern of marker placement on the back allows the spine to be split into functional areas as described previously by Muller et al. (2016). Thus, the markers overlying the spine and lateral areas were used to create the Lumbar Segment (LS) and Thoracic Segment (TS) (Fig. 4.3). Finally, to correctly identify movement events throughout the task, additional markers were placed on the outside edge of each shelf and on the edge of the box which was to be lifted.

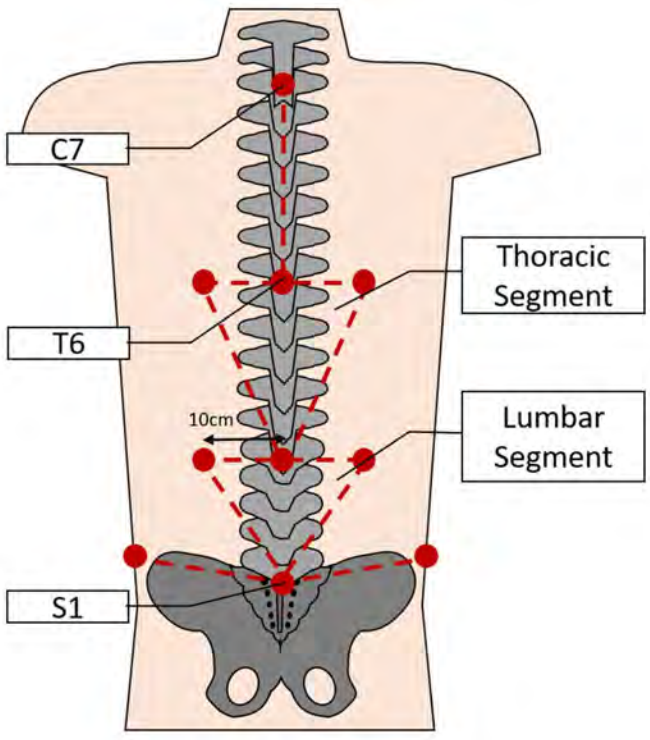


Fig. 4.3 – Approximate locations of the retroreflective markers on the back (lower limb markers not shown) and the subsequent segmental model used for analysis of spinal movements during the task (not to scale).

Throughout the lifting task, 3-D kinematic data were recorded continuously and sampled at 150 Hz. A trigger signal from the HDEMG amplifier was recorded alongside the kinematic data in order to allow synchronisation between the devices. All data were saved on a computer hard drive for offline processing.

Analysis of the 3-D data was completed using the BTS SMART software suite and custom analysis protocols (SMART Tracker, SMART Analyser; BTS Bioengineering, Italy). Raw 3-D data were tracked and labelled using custom kinematic models and any errors in the tracking were corrected to remove artefacts. Then, individual 3-D data points were interpolated and then filtered using a 5Hz Butterworth low-pass filter to ensure that each track was suitable for further analysis. Finally, the movements to each shelf were identified, and the 3-D tracks were cut in order to separate data into movement from S1-2 and S2-1. For the spinal segmental analysis, a reference axis was created for each segment (TS, LS), which were applied to virtual points in the centre of each segment. A Euler angle was calculated between these axes in order to understand how the segments moved in relation to each other throughout the task.

4.2.5 – Statistical Analysis

Statistical analysis was completed using Statistica Version 13.3 (Tibco, USA), with an alpha level set at 0.05, all statistical assumptions were met and η_p^2 were reported where relevant.

4.2.5.1 – Questionnaire Data

As described in Chapter three, questionnaire responses were evaluated according to their respective guidelines (Craig et al., 2003, Fairbank and Pynsent, 2000, Henry and Crawford, 2005, Osman et al., 1997, Waddell et al., 1993, Walsh et al., 2003). Any differences between groups in demographic and questionnaire data were identified and tested for significance using student t-tests.

4.2.5.2 – Motion Analysis

In this task, movement primarily occurred in the sagittal plane, thus for the motion analysis component of this study, the data considered involves only the movement around the horizontal axis in the sagittal plane. In order to understand differences in the movement strategy between groups, data were temporally normalised into 100 epochs representing 100% of the movement, and have been considered in terms of the shift from the first epoch. In order to achieve this, the angle between segments in the first epoch was considered as a zero-point, and was subtracted from each subsequent epoch, leaving just the deviation from epoch one. In order to test H4.2, any differences between groups for the movements were identified and tested for statistical significance using repeated measures ANOVA assessments with factors of group (LBP/CON) and time (100 epochs).

4.2.5.3 – HDEMG

To fully test H4.1 , analyses were conducted considering both absolute values (right and left) and, in line with several previous studies, comparing the most painful side for the LBP

group to the right side of the control group (Falla et al., 2014, Sanderson et al., 2019b). The choice of the right-hand side for CON participants is reflective of previous investigations using this side, and of the mono-planar nature of the task.

Where no significant differences were identified between the first and second epochs of each movement, and thus to improve clarity in the results, the mean values across the pairs of epochs have been reported. Differences between groups were identified using factorial ANOVAs with factors of Group (LBP/Control), Side (Left/Right), Movement (S1-2/S2-1), and Epoch (Lifting/Lowering).

Topographical maps of the muscle activity were created from the absolute RMS values for each group. As the spatial distribution data were presented in the form of an image, only qualitative analysis was possible. The maps were classified by two independent raters in terms of the pattern of the distribution of activity. Each rater classified each map as either 'diffuse activation', 'predominantly diffuse', 'cranial activation' or 'caudal activation'. Ratings were conducted independently and percentage agreement scores were calculated between raters (AS/EMV).

4.3 – Results

4.3.1 – Participants

Fourteen CON and 11 LBP participants completed the lifting task. There were no significant differences in the demographic characteristics between groups, with no differences identified in the mean age, BMI or sex distribution between groups (all $P>0.05$). The LBP group reported a mean current pain level of 2.59/10 (mild pain) and ODI score of 16.1 (minimal disability).

The questionnaire data revealed no significant differences in the level of physical activity between groups (measured by the IPAQ; $P>0.05$) or the level of mental health (measured by the DASS-21 and mental component summary (MCS) portion of the SF-36; both $P>0.05$). Significant differences were identified in measures related to back pain. The LBP group demonstrated higher levels of disability as measured by the ODI ($P<0.0001$) and lower levels of physical health as measured by the physical component summary (PCS) portion of the SF-36 ($P<0.0001$). Additionally, members of the LBP group showed higher levels of fear avoidance behaviours ($P<0.0001$) and pain catastrophising ($P=0.001$) related to their LBP symptoms. Full demographic information is presented in Table 4.1.

Characteristic		CON	LBP	P-Value
Age (Years)		27.36 ±11.4	32.45 ±16.3	-
Sex (# Males)		6	5	-
BMI		23.13 ±4.32	25.07 ±2.58	-
ODI (%) *		0.29 ±1.07	16.1 ±7.73	P<0.001
PCS *		6.07 ±7.50	19 ±10.13	P=0.001
IPAQ		72% High	82% High	-
DASS-21		9.29 ±9.69	21.82 ±29.59	-
FABQ *		3.38 ±6.31	27.28 ±11.31	P<0.001
PNRS	Current Pain	-	2.59 ±1.64	-
	Average Pain	-	3.36 ±2.06	-
SF-36	SF-PCS *	57.84 ±3.95	47.75 ±4.92	P<0.001
	SF-MCS	52.98 ±3.16	46.33 ±15.42	-

Table 4.1 – Sample demographics for the CON and LBP groups (mean ±SD). Where significant differences exist between groups the name of the outcome has been marked with an asterisk and a p-value is displayed. Physical component summary (SF-PCS), mental component summary (SF-MCS)

4.3.2 – Muscle Activity

In all analyses, there were significant systematic differences in the location of the centroid of muscle activity in the cranio-caudal direction (y-axis co-ordinate). Across both shelf movements, in both the analyses comparing the absolute data and the painful side analyses, the location of the y-coordinate of the centroid was systematically more cranial in the LBP group than in the control group. For the movement from S1-2, when comparing the absolute values, the average position for the y-coordinate of the centroid for the control group was 75.9±8.4mm cranial of the reference electrode, whereas for the LBP group, the centroid was 81.5±7mm cranial, a difference of 5.56mm ($F=12.13$, $P=0.0008$, $\eta_P^2 = 0.11$). Similarly, for the movement from S2-1 the centroid was 76.1±8.1mm cranial for the control group whereas it was 82.6±8.9mm for the LBP group, a mean difference of 6.47mm ($F=14.25$, $P=0.0003$, $\eta_P^2 = 0.13$) (Fig. 4.4). Similar results were identified in the comparison of the painful side and the right-hand side for the control group. On average the y-coordinate of the centroid was 4.02mm more

cranial in the LBP group for the movement from S1-2 (F=4.08, P=0.049, η_P^2 = 0.09), and 5.56mm more cranial for the movement from S2-1 (F=5.71, P=0.02, η_P^2 = 0.11).

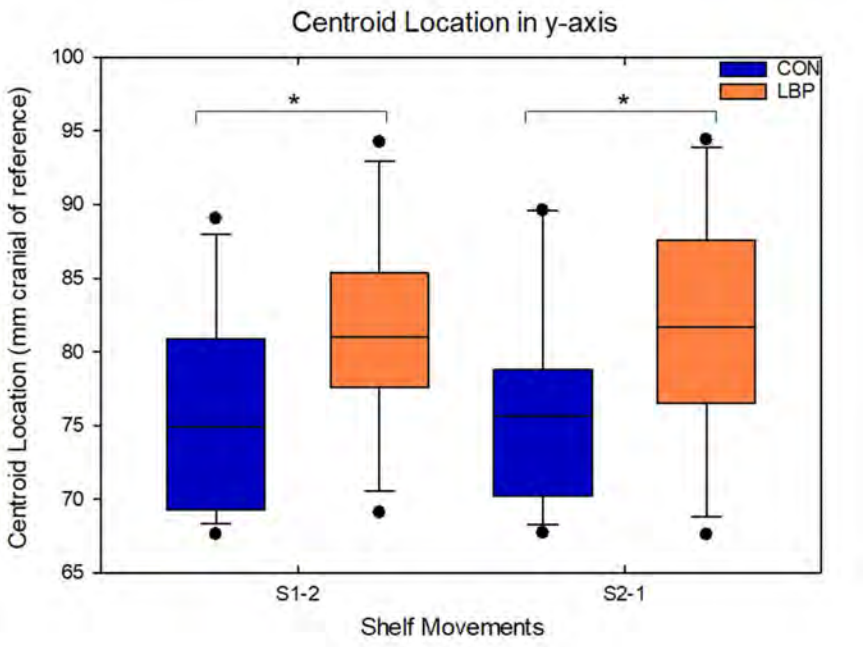


Fig. 4.4 – Demonstrating the location of the y –coordinate of the centroid in the cranio-caudal axis for movements from both S1-2 and S2-1 within the absolute data; significant differences between groups are indicated with an asterisk.

The difference in the spatial distribution of activity was reflected in the topographical maps of muscle activity across the lumbar and thoracolumbar ES. From observation of the maps, the LBP group displayed a more cranial distribution of activity, while the control group showed a more even distribution across the entire muscle (see Fig. 4.5 for a representative example). When two individuals independently (R1/R2) classified the distribution of activity, for movement S1-2 the LBP group showed a more cranial distribution of activity in 7/11 (R1) or 9/11 (R2) cases whereas the CON group showed an even distribution across the region in 11/14 (R1) or 13/14 (R2) cases (84% reviewer agreement). Similarly, for the movement from

S2-1 the LBP group demonstrated a more cranial distribution of activity in 6/11 (R1) or 8/11 (R2) cases and the CON group showed an even distribution in 12/14 (R1) or 11/14 (R2) cases (88% reviewer agreement). Fig. 4.6 shows the agreement between reviewers in classifying each participants' distribution maps.

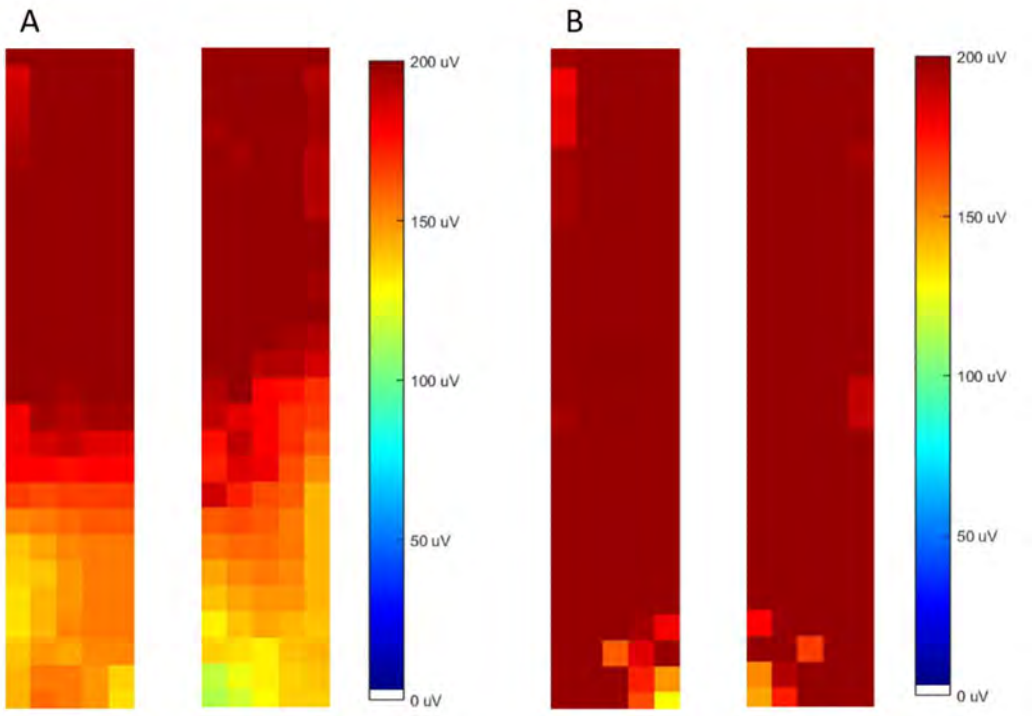


Fig. 4.5 – Representative examples of the topographical distribution of activity in the left and right grids for both (A) LBP and (B) CON groups.

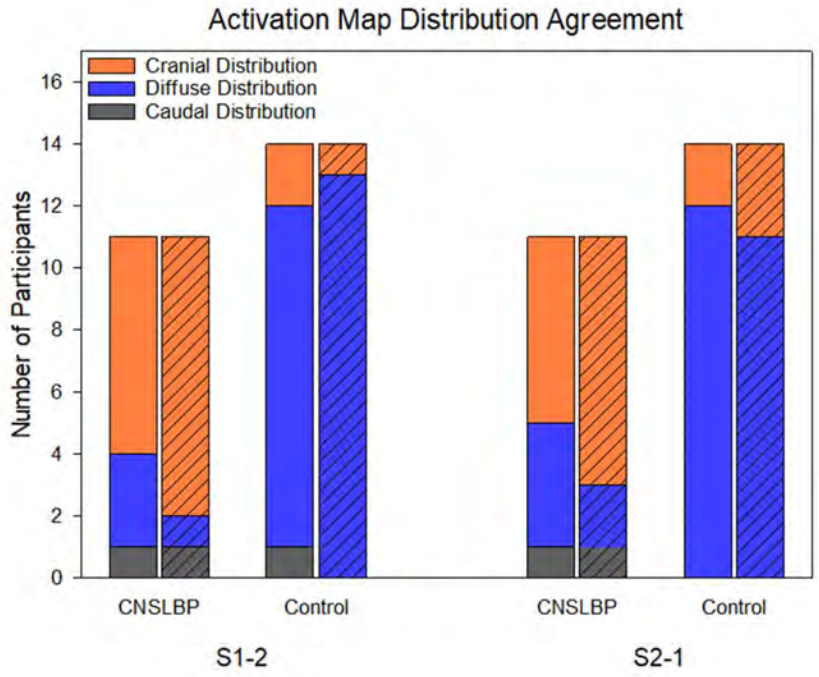


Fig 4.6 – Agreement between reviewers for the classification of the distribution maps. Rater 1 is identified by clear bars and Rater 2 is identified by hatched bars.

When comparing the absolute values for entropy to evaluate the homogeneity of muscle activity, the control group had systematically higher levels of entropy for both movement phases, indicating a more uniform distribution of activation across the EMG amplitude map. For the movement from S1-2, the control group had an entropy of 6.93±0.09 and the LBP group had an entropy of 6.89±0.11 ($F= 4.7$, $P=0.03$, $\eta_P^2 = 0.05$). For the movement from S2-1 the CON group entropy remained at 6.93±0.09, however the LBP entropy was lower again at 6.86±0.13 ($F=8.3$, $P=0.004$, $\eta_P^2 = 0.08$; Fig, 4.7).

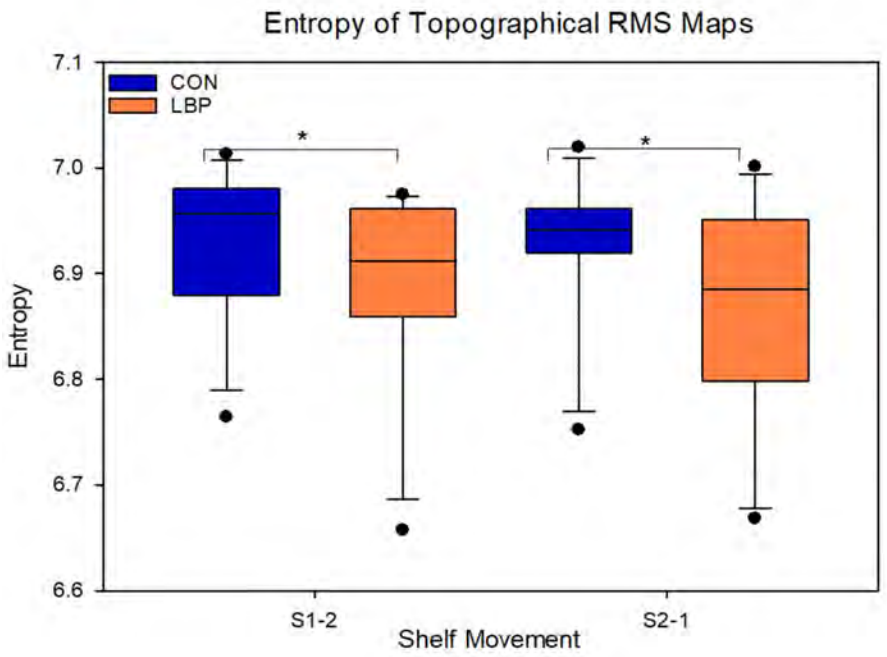


Fig. 4.7 – Depicting the entropy of the low back pain (LBP) and control (CON) groups. Significant differences are marked with an asterisk.

In this task, there was no significant difference in the normalised RMS between groups at any point during the task. Further, no significant differences were identified between groups for the location of the centroid in the medio-lateral x-axis in any condition. When comparing the most painful side of the LBP group to the right side of the CON group, there were no differences in mean x-coordinate of the centroid throughout the task (P=0.41); and no difference in the shift of the centroid in the x-axis throughout the lifting task (P=0.43).

4.3.3 – Kinematics

There was no difference in the movement pattern use to complete the task. Participants in both groups used the same lumbar-thoracic segment movement pattern to complete both

movements. No statistically significant differences were identified for the movement from S1-2 (P=0.81) or from S2-1 (P=0.24) (Fig. 4.8).

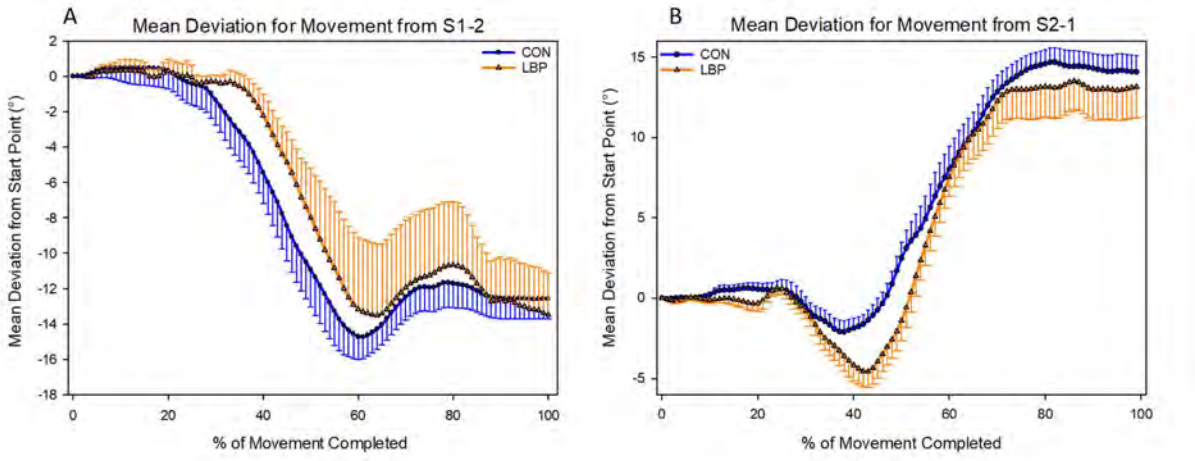


Fig. 4.8 – Depicting the mean deviations from the start position used by each group to complete each shelf movement (A – Shelf movement 1-2; B – Shelf movement 2-1)

4.4 – Discussion

This study uniquely demonstrates that people with minimal disability and mild CNSLBP utilise a more cranial and less diffuse distribution of erector spinae activity during a singular mono-planar lifting task, when compared to healthy controls. This effect was observed despite the identification of no statistically significant differences in the kinematic pattern between the lumbar and thoracolumbar segments. This study is the first to investigate both lumbar and thoracolumbar ES contributions to a lifting task in both the painful and non-painful side in participants with CNSLBP.

The participants recruited for this study were anthropomorphically comparable, with no significant differences in measures of BMI, age or biological sex between groups. Within the questionnaire results, there were also no differences between groups for the level of physical activity or for general mental health. However, understandably there were significant differences in measures designed to assess the impact of pain on day-to-day life. The LBP group reported higher levels of disability, pain catastrophising and fear avoidance behaviours than the control group, consistent with previous research (Fairbank and Pynsent, 2000, McWilliams et al., 2015, Waddell et al., 1993). However, with the mean ODI score of 16/50 and average pain at the time of data collection of 2.6/10, it is suspected that this group has only mild levels of pain and were highly functional (Breivik et al., 2008).

Evidence from previous studies has shown that people with CNSLBP demonstrated reduced range of motion in spinal flexion when compared to healthy controls (Shojaei et al., 2017a, Falla et al., 2014). This is likely due to the controlled nature of the task, as the participants received a demonstration of the movement and then were allowed to practice with an unweighted box to ensure that they completed the task correctly. Furthermore, they were

asked to complete the task to the beat of a metronome to facilitate standardisation. While other studies have similar pre-task training, as this task was short, it is possible that participants did not have the time to alter their movement strategy as pain was provoked or myoelectric fatigue developed as may be the case in longer tasks, however the myoelectric manifestations of fatigue were not formally measured here. Therefore, if the task were to be sustained for several minutes, then it is possible that differences may become apparent. Furthermore, while this task design has not been investigated in a CNSLBP population, an investigation in a healthy cohort reported low variability in movement, indicating that a movement with few repetitions might be expected to have little variability between subjects (Peach et al., 1998).

Consistently within the results of this study, there was less diffuse and more cranially focused ES activity in the LBP group. The differences seen from the topographical EMG amplitude maps were supported by the statistically significant differences in the location of the y-coordinate of the centroid and entropy between groups. Specifically, those with CNSLBP generally performed the lifting task with greater activity in cranial regions of the thoracolumbar ES relative to the lumbar ES, resulting in greater heterogeneity of activity across the entire region examined. These findings suggest that participants in the LBP group engaged lower thoracic portions of the ES, that is the *iliocostalis lumborum pars thoracis* or the *longissimus thoracis pars thoracis*, to complete a targeted lumbar lifting task, relative to asymptomatic people.

It is important to consider that these results were not uniform across the entire group of participants, and members of both the CNSLBP group and CON group did not follow the identified trends. It is difficult to speculate on the reasons why these individuals may not show the same activation patterns; the reasons for these individual differences could range from

biomechanically different lifting techniques to fear of movement from individuals experiencing CNSLBP, or even that pain in those individuals is primarily influenced by psychological or social factors and less represented biologically. It is also pertinent to consider that centroid and entropy outcomes are both relatively novel analyses with largely untested reliability, especially for the ES. Entropy, for example, uses arbitrary units as a scale so it is difficult to determine the magnitude of change required to represent a meaningful difference between groups (Rampichini et al., 2020). Previous studies which have used entropy to describe surface EMG changes in the presence of pain have described changes significant changes as small as 0.2AU (Falla and Farina, 2008b, Januario et al., 2017, Martinez-Valdes et al., 2019). Therefore, while the results described here are slightly smaller, with differences between groups of <0.1AU, they remain similar to previous reports. Furthermore, within this study the change in distribution of activity was identified first via objective visual comparison of EMG amplitude maps; then this observation was supported with the entropy measure as a quantification of signal complexity and the location of the y-coordinate of the centroid. Each of these analyses represents a weak level of evidence alone, however the combination of analyses begins to reveal a consistent result indicating a generally more cranial activation of the ES in individuals with CNSLBP.

The cranial shift of activity seen in the LBP group relative to the control group, likely implies the utilisation of less biomechanically favourable muscle fibres to complete the lifting task (Bogduk, 2005). The structure of the ES in the lumbar region is laminated. The deepest and most medial fibres of the ES connect L5 to the PSIS, with fibres to each subsequent lumbar vertebrae forming progressively more superficially and laterally (Bogduk, 2005, Christophy et al., 2012, Bogduk, 1980). Thus, activation focused in the more cranial portions of the muscle is representative of primarily using the fibres extending to the higher lumbar vertebrae rather than the whole muscle. In this task due to the weighted box, which was held anterior to the

participant, the forces through the lumbar spine were multiplied when the participant leant forward to complete the task (Han et al., 1995). Previous studies which have investigated the effect of dynamic lifting on this region have reported increases in both the L5/S1 sheer forces and activity in the lumbar extensors (Arjmand and Shirazi-Adl, 2005). However here the activity was identified to be focused more cranially in the LBP group, potentially reducing the muscle fibres which were utilised to resist the increased sheer forces at the lower lumbar vertebrae.

The topographical redistribution of EMG activity within a muscle, during a fatiguing task, has also been observed in the *trapezius* muscle (Barbero et al., 2016). This phenomenon appeared to be correlated with the duration of the task and appears to be important to maintain the motor output (Farina et al., 2008). Notably, previous investigations including both dynamic and static tasks in presence of neck pain, consistently showed a redistribution of upper *trapezius* activity in a caudal direction (Falla et al., 2010, Falla et al., 2017). When considering the findings reported here, the variation in muscle activation occurs in a different manner but can be considered the output of the same adaptation strategy aimed to avoid pain or overload. Although, it is not possible to exclude that regional nociception can inhibit the muscle activity in some specific anatomical regions. In both cases the underlying physiological adaptations can play an important role in the clinical course of musculoskeletal pain.

4.4.1 - Reliability

As discussed in section 1.4.4 and again in the interpretation of results in Chapter 3, the reliability of HDEMG and the associated outcomes has not been established in the context of individuals with CNSLBP. The results presented in this study demonstrated small effect sizes but as these data were supported by the recruitment of an adequate sample, these results may

represent a novel finding in this population. However, as described in Chapter 3, the confidence in the strength of this finding is limited due to the potential inconsistency in the technique (Guyatt et al., 2011c, Guyatt et al., 2008). Further work which establishes reliability for HDEMG in the lumbar region for a population with CNSLBP would greatly increase the confidence in these findings.

4.4.2 – Strengths and Limitations

This study is the first to assess muscle activity comprehensively over the lumbar and thoracolumbar region of the ES bilaterally during a lifting task. This allowed for the measurement of the effect that occupational lifting can have on people who already experience CNSLBP; granting a deeper insight into the distribution of activity across the entire muscle region, and allowing the identification of a differing activation pattern. The findings of this study are reported in line with the STROBE statement, and it is expected that a risk of bias assessment using the NOS tool from Chapter two would identify a low risk of bias in this study.

A relatively small sample was used for this study, which might account for some of the variability within the data. Nevertheless, the sample size was sufficient to reveal significant differences between groups. Additionally, the symptomatic participants were highly functional and reported only mild levels of CNSLBP and disability; so, it is not known how these results would be affected by more severe CNSLBP symptoms or higher disability. Therefore, as with the results from Chapter three, it might be difficult to generalise these results to patients with more severe symptoms (Arendt-Nielsen and Graven-Nielsen, 2008, Mannion et al., 2000).

This task was designed to assess the effect of lifting a light load by an individual who has CNSLBP; however, most occupational lifting tasks would comprise of repeated lifting, as in a factory setting, or multidirectional lifting. Nevertheless, our focus was to comprehensively

evaluate muscle behaviour and spinal movement during a single lift, without the presence of myoelectric manifestations of fatigue or provoked pain which could confound interpretation of the results, although as fatigue was not measured here this is slightly speculative. It must also be considered that the weight of the box was standardised at 5kg and not altered based on participants anthropomorphic characteristics, so the relative load per participant is likely to be varied. This difference in relative load could be due to a variety of factors including (but not limited to) trunk strength, age, height, severity of LBP symptoms, and so would be difficult to precisely control for. As such, this task was instead intended to represent a functional task (*e.g.* lifting shopping) which would not be altered based on the relative strength of the participant. One final potential limitation of this study is in the qualitative interpretation of the spatial distribution data. As both reviewers are investigators in the study, there is a potential source of bias based on prior expectations, however reviewers were blinded to the group of the participant, and reviewed independently with good levels of reviewer agreement (>80%).

4.5 – Conclusions

Participants with mild CNSLBP utilise a different motor strategy to complete a lifting task, which was characterised by a less diffuse, less homogenous, and more cranially focussed activation of the ES. This difference in muscle behaviour was observed despite a consistent movement strategy between groups. This distribution was identified in Chapter three during a static task and now in a simple, monoplanar dynamic task; further research should be conducted to assess the stability of this result during complex multiplanar movements.

CHAPTER 5

REDUCED VARIABILITY IN ERECTOR SPINAE ACTIVITY IN PEOPLE WITH LOW BACK PAIN DURING A DYNAMIC 3-D LIFTING TASK

This Chapter reports in full a manuscript which has been prepared for publication and is under review for publication in the Clinical Journal of Pain. Changes have been made in the text of this Chapter for the purposes of a thesis, specifically;

- The introduction has been edited to reflect the content of previous Chapters in this thesis and avoid repetition
- Where overlapping occurs, areas of the methodology have been reduced to reflect the previous elaborations in Chapters three and four
- The discussion and conclusion have been edited to increase cohesion between linked studies in later Chapters.

However, the majority of the text in this Chapter reflects the submitted manuscript verbatim.

Presentations

1. **Sanderson, A.,** Cescon, C., Heneghan, N.R., Rushton, A., Barbero, M., Falla, D. What is the Influence of Low Back Pain on Muscle Activity and Movement during a Cyclical Dynamic Task? Pain Science in Motion III (PSIM). Savona, Italy, May 31-2, 2019.

2. **Sanderson, A.,** Cescon, C., Heneghan, N.R., Rushton, A., Barbero, M., Kuithan, P., Falla, D. How does Low Back Pain Influence Muscle Activity during a Cyclical Dynamic Lifting Task? Physiotherapy UK 2019. Birmingham, UK, 1st – 2nd November 2019.

3. **Sanderson, A**., Cescon, C., Kuithan, P., Heneghan, N.R., Rushton, A., Martinez-Valdes, E., Barbero, M., Falla, D. Using HDEMG to understand the influence of low back pain on the distribution of muscle activity during a 3-D dynamic task. XXIII Congress of the International Society of Electrophysiology and Kinesiology (ISEK). Pre-Congress Workshop. Virtual Congress. July 12-14, 2020. (Accepted)

5 – Abstract

The results of Chapters three and four identified clear differences in the distribution of activity. People with mild CNSLBP have been shown to use a more cranially focussed and less diffuse muscle activation strategy to complete simple dynamic and static tasks. This cross-sectional study aimed to investigate the distribution of activity in the lumbar ES during a complex, dynamic multiplanar task. Activity from 14 LBP (32.14 ± 14.6 years) with mild-moderate CNSLBP (2.68 ± 2.03/10) and 15 CON (26.87 ± 11.1 years) was recorded continuously using four high-density EMG grids (two bilaterally) affixed over the ES. Motion data was recorded using reflective markers adhered over the trunk. The task involved the cyclical lifting of a 5kg box from a central anterior shelf to five anterior and lateral shelves, returning to the first shelf between each sequential movement. As in previous studies in this thesis, the LBP group systematically used a muscle activation strategy, characterised by less diffuse and more cranially focussed contractions. In addition, in the aspects of the 3-D movements which were distal to the central shelf, LBP participants exhibited less variation between sides in the distribution of the contraction produced. Across the whole task, there were few meaningful differences in the movement patterns between spinal segments, but LBP participants found the task more exerting. People with CNSLBP used a motor control strategy which focussed on less variable, less diffuse and more cranially focussed contractions. Despite this, there were few consistent differences in the movement pattern, suggesting the use of less biomechanically favourable portions of the ES to complete this complex multiplanar task.

5.1 – Introduction

Chapters three and four have demonstrated that people with CNSLBP appear to display an altered motor control strategy to simple functional tasks. This strategy is characterised by a less diffuse and more cranially focussed distribution of activity demonstrated during simple tasks. These tasks have included static lumbar extension and a simple, monoplanar lifting tasks. The review in Chapter two indicated a wide variety of tasks which have previously been used to investigate the magnitude of muscle activation in people with CNSLBP. However, the tasks examined thus far in this thesis do not fully reflect the multidirectional nature of these tasks. Therefore, a multidirectional task is required in order to ascertain if this motor control strategy is consistently employed across functional movements.

Manual occupational tasks, including repeated and routine heavy lifting, presented conflicting evidence for the persistence of CNSLBP symptoms (Kwon et al., 2011; Silvetti et al., 2019). Additionally, the presence of CNSLBP has repeatedly been demonstrated to affect participants' movement patterns (Shojaei et al., 2017a), perception of pain (Kuithan et al., 2019), and spinal stability during lifting tasks (Hemming et al., 2018).

However, as discussed in previous Chapters, studies which have examined the distribution of muscle activity during lifting tasks have used monoplanar tasks, bipolar electrodes and limited muscle region of interest (Falla et al., 2014, Fabian et al., 2005, Lariviere et al., 2002b). Studies have incorporated monoplanar movements, which might not fully reflect the 3-D nature of functional human movement, for example in a study where contractions to produce movements in three planes was assessed, these contractions were isometric and strictly limited to each cardinal plane (Ng et al., 2002). Furthermore, previous results recording muscle activity during lifting tasks have been limited to the specific region of interest investigated, e.g.

activation measured unilaterally (Falla et al., 2014; Lariviere et al., 2002). The study reported in Chapter four investigated muscle activity bilaterally in the lumbar and thoracolumbar region, however in this instance the task involved a singular monoplanar lifting task, which was not reflective of repetitive, multiplanar functional lifting (Sanderson et al., 2019a).

Thus in the current study the aim was to perform a more comprehensive investigation of the location, distribution and variability of ES activity by (1) evaluating lumbar and thoracolumbar ES muscle activation bilaterally using HDEMG, and (2) quantifying any differences in the 3-D motion in the lumbar and thoracolumbar regions as people with and without CNSLBP performed a multiplanar lifting task.

5.1.1– Objectives

The objectives of this Chapter were to investigate the spatial distribution, and redistribution, of bilateral lumbar and thoracolumbar ES activity in people with CNSLBP and pain-free controls during a complex multiplanar functional lifting task; and identify any differences in the 3-D movement strategy

5.1.2 – Hypotheses

H5.1 - It was hypothesised that people with CNSLBP would demonstrate the same altered motor control strategy as shown in previous Chapters, characterised by a more cranially focussed and less diffuse distribution of activity.

H5.2 - It was also hypothesised however that this would reflect no difference in the movement strategy compared to control participants given the standardised nature of the task.

5.2 – Methods

This study was an observational cross-sectional study, and is reported in line with the STROBE statement. Data collection was conducted at a laboratory within CPR Spine, University of Birmingham. Recruitment and data collection for this study was completed between June 2017 and March 2018 and data was collected within one session for each participant. Ethical approval for this study was granted by the University of Birmingham Ethics Committee (ERN_16-1389B, Appendix 9). Participants gave written informed consent prior to data collection and all procedures were completed in accordance with the Declaration of Helsinki. An *a-priori* power calculation was completed as described in previous Chapters using a small effect size (0.1), and a sample of 36 was recommended.

5.2.1 – Participants

Participants were recruited according to the same inclusion and exclusion criteria described in previous Chapters.

5.2.2 – Questionnaires

The questionnaires used to characterise the participant groups was near identical to those used in Chapter four, with the addition of the Borg RPE scale as described in Chapter three at the end of the experimental task.

5.2.3 – Experimental Task

The experimental task consisted of a cyclical lifting task of a 5kg weighted box between six shelves situated anteriorly and laterally to the participant. As ergonomic interventions have been demonstrated to influence lumbar loading, the location and height of each shelf was adjusted for each participant, based on palpated anthropomorphic characteristics selected from pilot feedback as described in Chapter four (Faber et al., 2007, Motamedzade et al., 2013). Shelf heights, and the distance from the foot-base to the anterior shelves were determined as described in Chapter four. Measured from the midpoint of the foot-base the lateral shelves were situated half of the distance between the right and left olecranon processes, with the arms abducted to shoulder height (Fig. 5.1).

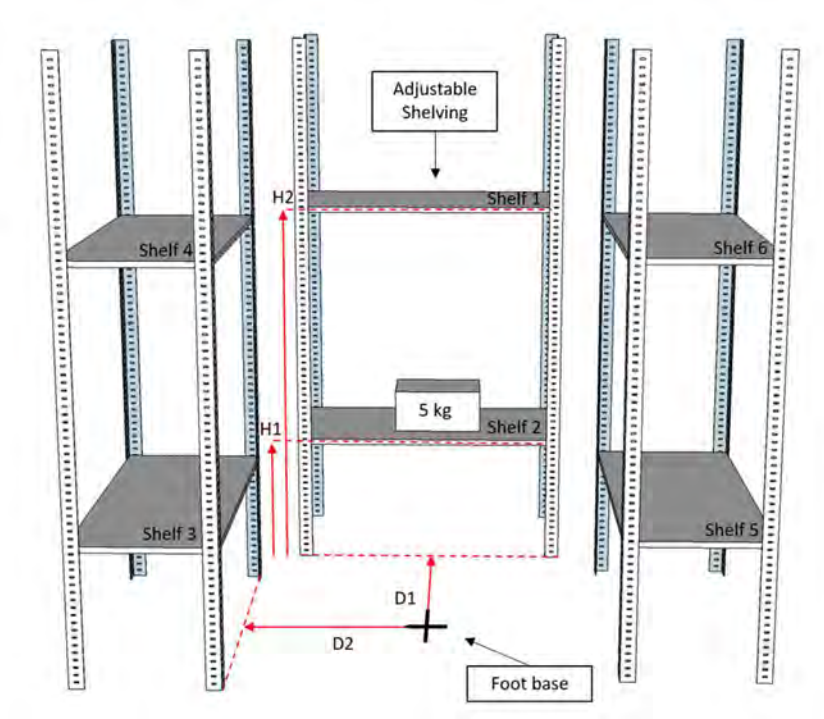


Fig. 5.1 – Schematic of the task set-up depicting the adjustable shelving and the foot-base. The distance of the shelves from the foot-base are shown by D1 – acromion to ulnar styloid process and D2 – half of the inter olecranon distance. The height of the shelves are shown by H1 (lateral femoral epicondyle height) and H2 (manubriosternal angle height) (not to scale).

During the task, participants performed ten cycles of lifting a 5kg box (35.5 cm x 29 cm x 13.5 cm) between six shelves at the same 2s pace as described in Chapter four. The lifting movement involved a basic pattern of lifting to a sequential shelf, returning to the starting position on shelf one (S1), before moving to the next sequential shelf (S2-S6), with rests between movements. Therefore, an example of a sequence of movements would be from S4-S1, rest, S1-S5. Each cycle of lifting involved a total of ten movements, one from the central shelf to each distal shelf, and one from each distal shelf back to the central shelf, correctly performed the entire task comprised of ten repetitions of ten movements. This movement pattern, involving the repeated lifting of a standardised weight (5kg) in a 3-D multiplanar manner was designed to better reflect a task of daily life or functional lifting.

The task was explained by researchers using standardised instructions, and a demonstration of one complete cycle was given. Participants were asked to not move their feet and limit knee movement, but were given no further instructions regarding lifting technique. Participants were then allowed to practise one complete timed cycle with an unweighted box to ensure that the pattern and lifting strategy at the knees and feet were correct. The task was completed in one continuous acquisition lasting approximately seven minutes and following completion participants were asked to use the Borg RPE scale to rate how exerting they found the task to be (Borg, 1998).

5.2.4 – Experimental Set-Up

5.2.4.1 – Electromyography

HDEMG signals were recorded from four grids across the lumbar and thoracolumbar region in an identical manner to the technique described in Chapter four. The electrode

placement is depicted in Fig. 5.2, and reference electrodes were placed on S1 and the right medial malleolus.

5.2.4.2 – Motion Analysis

Motion data were recorded from reflective markers on the trunk in an identical manner to the technique described in Chapter four. The locations of kinematic markers are depicted in Fig. 5.2.

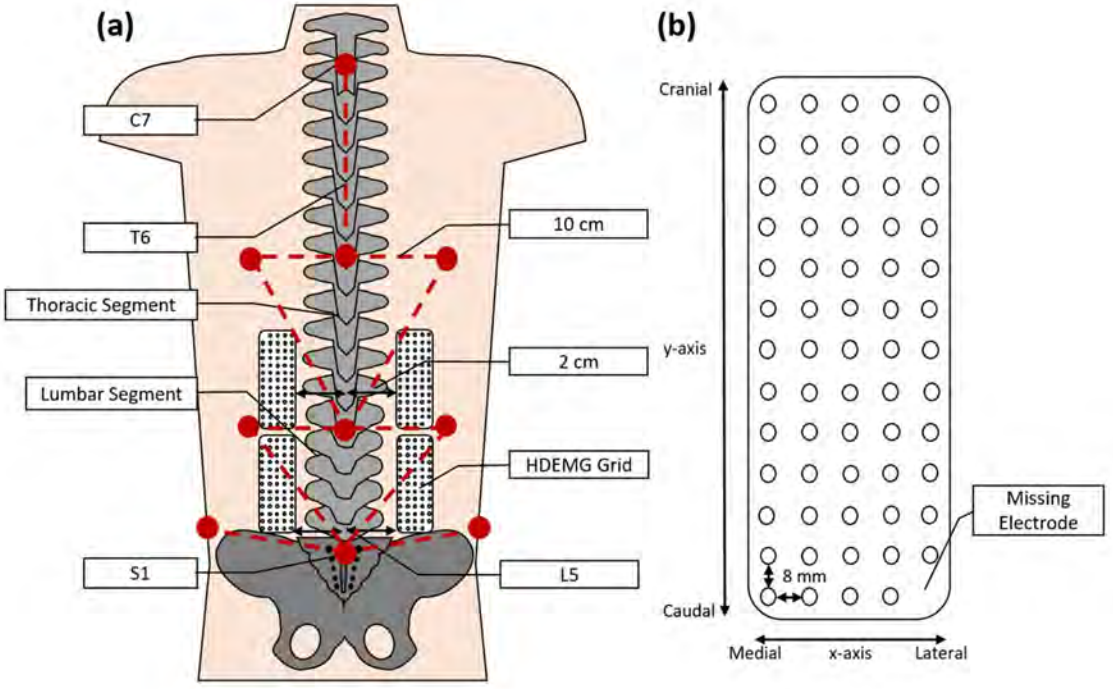


Fig. 5.2 – Depicting the combined HDEMG and kinematic experimental set-up for data collection. Showing (a) the approximate positioning of the HDEMG grids and reflective markers (marked in red) over the lumbar and lumbothoracic regions. The HDEMG grids were positioned 2cm lateral to the spinous processes and spaced 5mm between grids. The retroreflective markers were positioned over the spinous processes and 10cm lateral, this arrangement allowed for the creation of two trunk segments, marked. (b) a schematic of the HDEMG electrode grid depicting the interelectrode distance, the positioning of the x- and y- axes and showing the location of the missing electrode (not to scale).

5.2.5 – Statistical Analysis

Statistical analysis was completed using Statistica Version 13.3 (Tibco, USA), with an alpha level set at 0.05, all statistical assumptions were met and η_p^2 were reported where relevant. Unless specifically stated otherwise, all reported group results were supported by individual comparisons which have not been individually reported for reasons of brevity and clarity, where this is not the case, individual results have been reported.

5.2.5.1 – Participant Characteristics

Questionnaires were scored and assessed as described in Chapter four.

5.2.5.3 – Motion Data

Raw data were tracked and processed as described in Chapter four to create the LS and TS segments, before further processing was applied for the additional movements. Using the varying distance between the markers on the box and on each shelf, movements to and from each shelf were reconstructed. The 3-D tracks were cut between each shelf movement and time was normalised for each movement to the same shelf.

To test H5.2, motion data was normalised into 101 epochs for each cycle of each movement, representing a starting point and 100% of the movement from the origin shelf to the target shelf. Where participants had made an error in the movement task, or the 3-D data was lost, the analysis software discarded data for that cycle of the specific movement and replaced it with data from the subsequent cycle. As most participants had made an error in the first or last cycle, often only nine cycles of movement data were available, so in order to assess gross

changes in movement data was averaged into three sets of three completed cycles. The first set of cycles represented the first three correctly completed repetitions (C1-3), subsequent cycles were split into C4-6 and C7-9.

Motion data were considered in both absolute motion pattern across cycles, and in terms of the shift from the first epoch within each group of cycles. To investigate the shift, the value of the first epoch was subtracted from each subsequent epoch to understand how the position had changed throughout the task. To assess differences between groups, repeated measures ANOVAs were used for each movement with factors of group (n=2; LBP/CON), cycle (n=3; C1-3, C4-6, C7-9) and time (N=100, 1-100%).

5.2.5.2 – HDEMG Data

Initial HDEMG processing was completed as described in Chapter four, but as the task in this study required additional movements, further processing was required.

Kinematic data were used to identify all movements to and from each shelf and the signals were divided accordingly. EMG data for any movements where the participants made a mistake in the movement pattern were discarded *in situ* and analysis recommenced at the next correct movement. Within each cycle (C1-C10) of each shelf movement, the signals were divided into two epochs of 2s each, termed epoch one (E1) and epoch two (E2). For each signal and epoch, the RMS was calculated and plotted on a topographical map, representing the spatial distribution of activity within the investigated region. As in previous studies, the location of the centre of muscle activity (centroid) in both the x- and y-axes was calculated from these maps (Tucker et al., 2009, Falla et al., 2014). The entropy of the signals was also calculated for each epoch, this measure assesses signal complexity and is a measure of the spatial homogeneity of

signals (Martinez-Valdes et al., 2019). The RMS and entropy were averaged across each large grid to calculate single values for each side, indicating one mean value for each side.

To fully test H5.1, analyses were conducted using data from both right and left sides independently and combined. In some analyses, data have been assessed both in terms of their order in time, and their distance from S1. Thus, epochs have been grouped in their temporal order, where E1 is the first half of a movement, and their spatial order in terms of if movement within the epoch is proximal or distal to S1. Similarly, muscle activity across movements were assessed and grouped according to the anatomical location of the muscle (left/right), or if the movement is anterior, or to the ipsilateral or contralateral side for the muscle. Where no differences, or no consistent differences, were identified across cycles, the cycles have been averaged to create a mean value representing activity in the muscle for that shelf movement.

The centroid data was assessed in terms of the absolute location, the shift in location from the first epoch of the first movement for each side, and the difference in the absolute location between sides. As this task was 3-D in nature, to fully assess how movements were produced in different directions, it was important to assess the difference in centroid location between sides. To do so, the absolute location of the centroid in the left grid was subtracted from that of the right for each axis. Thus, in this analysis, for both barycentre's neutral values indicate that both centroids were at the same position in their respective axes. RMS data was analysed both in terms of the absolute values and normalised values across time. To calculate the normalised values, the first epoch of the first movement for each side was calculated as 100% of the activation, and subsequent epochs and cycles were calculated in reference to this initial value.

Significant differences between groups were identified using factorial ANOVAs, and factors could include movement (n=10; S1-2 – S6-1), cycle (n=10; C1 – C10), type (n=2; LBP/CON), side (n=2; left/right), muscle movement direction (n=3; anterior, ipsilateral, contralateral), epoch (n=2; E1/E2) or epoch distance (n=2, proximal to S1/distal to S1). In order to maintain the stability of the analysis, not all factors were used simultaneously, and often analyses were split by factors such as movement and epoch distance and assessed individually.

5.3 – Results

5.3.1 – Participants

Fifteen CON and 14 LBP participants were recruited, and completed the data collection process with complete datasets. Data was lost from an additional 12 participants (five CON/seven LBP) due to equipment failure during data collection on the kinematics system, precluding any analysis. This was primarily caused by system crashes relating to the kinematic data acquisition, which precluded the identification of different movements within the EMG data.

Participant characteristics were the same between groups with no differences between groups for anthropomorphic features such as height, weight, BMI or for participant sex or age (all $P>0.05$) (Table 5.2). No differences were recorded between groups for the level of physical activity or measures of mental health ($P>0.05$). However, as expected, the LBP group showed increased, yet minimal disability of 15.36% ± 6.95, compared to the CON value of 0.27 ± 1.0 ($P<0.0001$). Within the LBP group, participants recorded mild average pain on the day of testing of 2.68/10 ±2.03, and retrospectively reported a moderate average pain over the previous month of 5.93/10 ±1.69. LBP participants also demonstrated increased fear avoidance (LBP – 29.21 ± 13.51, CON – 3.13 ± 6.14) and pain catastrophising behaviours (LBP – 17.5 ± 9.37, CON – 6.27 ± 7.27) ($P<0.001$ for all). Finally, differences were identified in the physical component of the SF-36 (LBP – 57.94 ± 3.83, CON – 48.63 ± 4.76; $P<0.0001$), but not in the mental component ($P>0.05$).

Characteristic		CON (n=15)	LBP (n=14)	P-Value
Age (Years)		26.87 ± 11.1	32.14 ± 14.6	-
Sex (# Males)		6 Male	7 Male	-
BMI		23.12 ± 4.2	25.39 ± 3.6	-
ODI (%) *		0.27 ± 1.03	15.36 ± 6.95	P<0.0001
PCS *		6.27 ± 7.27	17.5 ± 9.37	P=0.001
IPAQ		73.33% High	85.71% High	-
DASS-21		10.53 ± 10.51	18.29 ± 26.91	-
FABQ *		3.13 ± 6.14	29.21 ± 13.51	P<0.0001
PNRS	**Current Pain**	-	2.68 ± 2.03	-
	Average Pain	-	5.93 ± 1.69	-
SF-36	**PCS ***	57.94 ± 3.83	48.63 ± 4.76	P<0.0001
	MCS	52.13 ± 4.48	47.51 ± 14.07	-

Table 5.1 – A summary of the participant characteristics, unless otherwise stated all values are listed as mean ± standard deviation. Results for the IPAQ reflect the proportion of participants who were identified as having high levels of activity. Where significant differences occurred between groups, the outcome is marked with an asterisk and a p-value is stated.

Participants in the LBP group found completing the task to be more exerting, as measured by the Borg scale, with an average reported exertion at the end of the task of 12.86 ±1.7. CON participants reported a mean exertion of 10.87 ±2.17, a difference of 1.99 between groups (P=0.01).

5.3.2 – Muscle Activity

Bilaterally, across all cycles, for all movements and epochs the LBP group had a systematically more cranial Y-barycentre of muscle activity (P<0.05 for all comparisons, Fig. 5.3). On average, the Y-barycentre of the centroid was 3.94mm more cranial for the LBP group than the CON group.

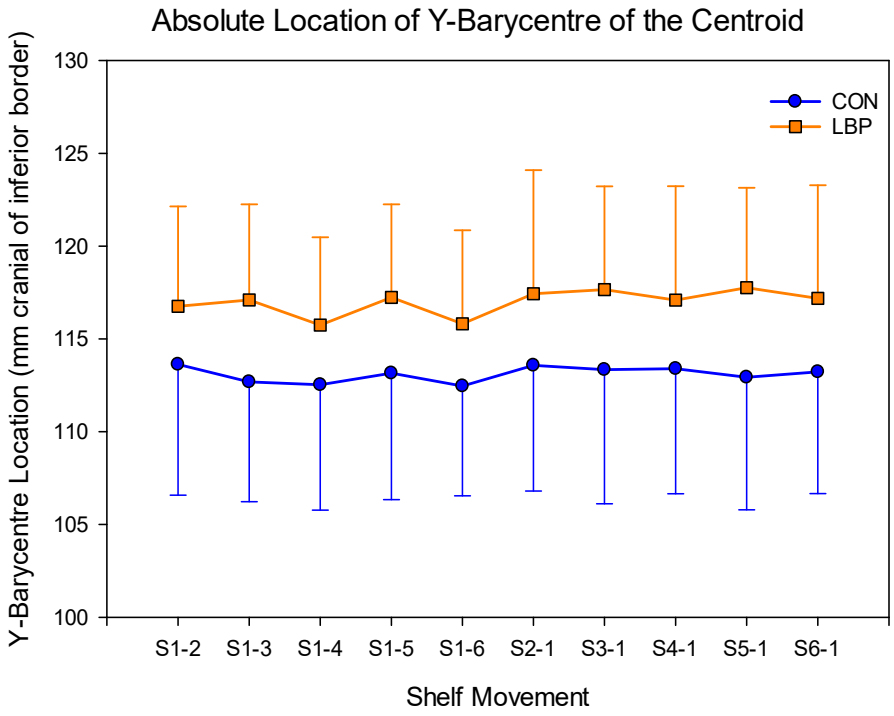
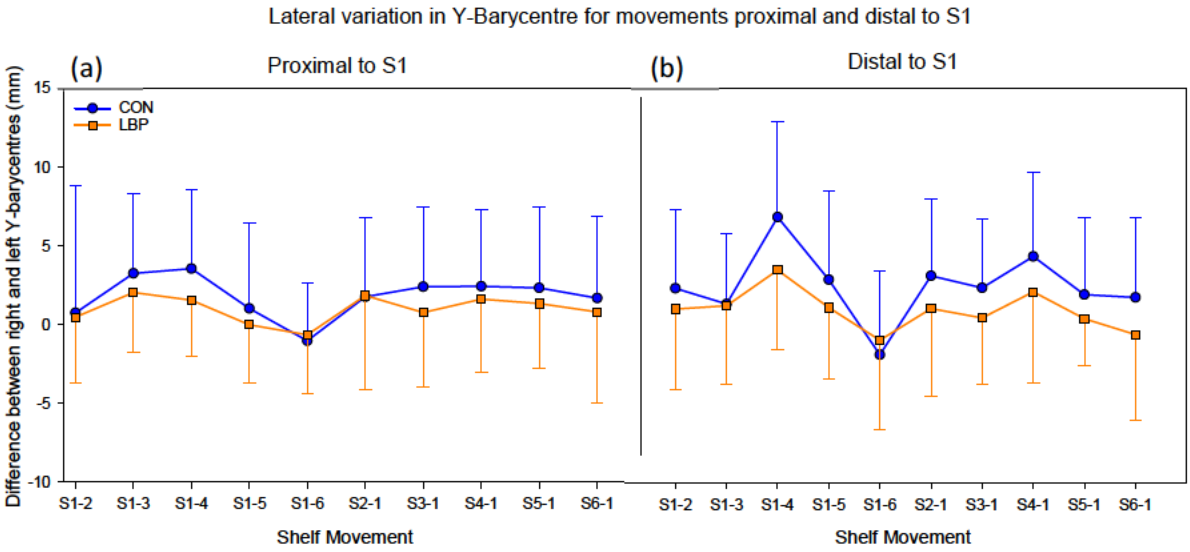


Fig. 5.3 – Demonstrating the absolute location of the barycentre of the centroid in the Y (cranio-caudal) axis for all movements across the duration of the task. The data here is arranged first for movements away from S1 and then for movements returning to S1.

There were no differences between groups in the absolute variability in the Y-barycentre location for any movement or side across the task ($P>0.05$). However, when assessing the differences in the location of the Y-barycentre between sides, the CON group showed more variability in the cranio-caudal y-axis between the right and left sides across movements compared to the LBP group. A significant interaction was identified in both lifting and lowering epochs, confirming that a different strategy was used by each group to complete each movement (E1 – $F= 2.29$, $P=0.02$, $\eta_P^2=0.01$; E2 – $F=3.31$, $P=0.0004$, $\eta_P^2= 0.01$). When the epochs were considered instead for their proximity or distality to Shelf 1, this interaction changed. In this analysis, there was no significant difference between groups in the right-left variability in

movements proximal to S1 (P>0.05; Fig. 5.4a). However, in the distal portions of movements,



the CON group demonstrated much greater variation in the centroid location between sides (F= 3.7, P<0.0001, η_P^2= 0.01; Fig. 5.4b).

Fig. 5.4 – The lateral variation between the right and left grids in the location of the Y-barycentre in movements (a) proximal to shelf one (S1) and (b) distal to S1. In this graph, a more positive number indicates a more cranial centroid on the right grid, a more negative number indicates a more cranial centroid on the left grid. The data is arranged first for movements away from S1 and then for movements returning to S1.

Absolute results for the location of the X-barycentre were somewhat less consistent, with systematic differences between groups in the absolute location of the centroid found in 13 out of 20 assessed conditions (P<0.05, 10 movements, 2 sides). When investigating the absolute shift of the centroid, these results were clearer with a greater displacement in the centroid identified in movements to and from S2 only for those in the LBP group (P=0.028 S1-2; P=0.046 S2-1; P>0.05 for all others). When assessing variation between the right and left X-barycentre, similar results were identified to those of the Y-barycentre. In the phases of movements proximal to S1, while systematic differences were apparent between groups (F= 6.24, P=0.012, η_P^2= 0.002), there was no difference for how each group completed the shelf

movements (P=0.35). However, in the phase of movement distal to S1, there were both significant differences between groups (F=8.55, P=0.0033, η_P^2= 0.003) and in how groups completed each movement, with the CON group showing greater variation (F=3.09, P=0.0012, η_P^2= 0.01). Fig. 5.5 illustrates the compiled mean locations of the centroid location on the right and left sides for all movements.

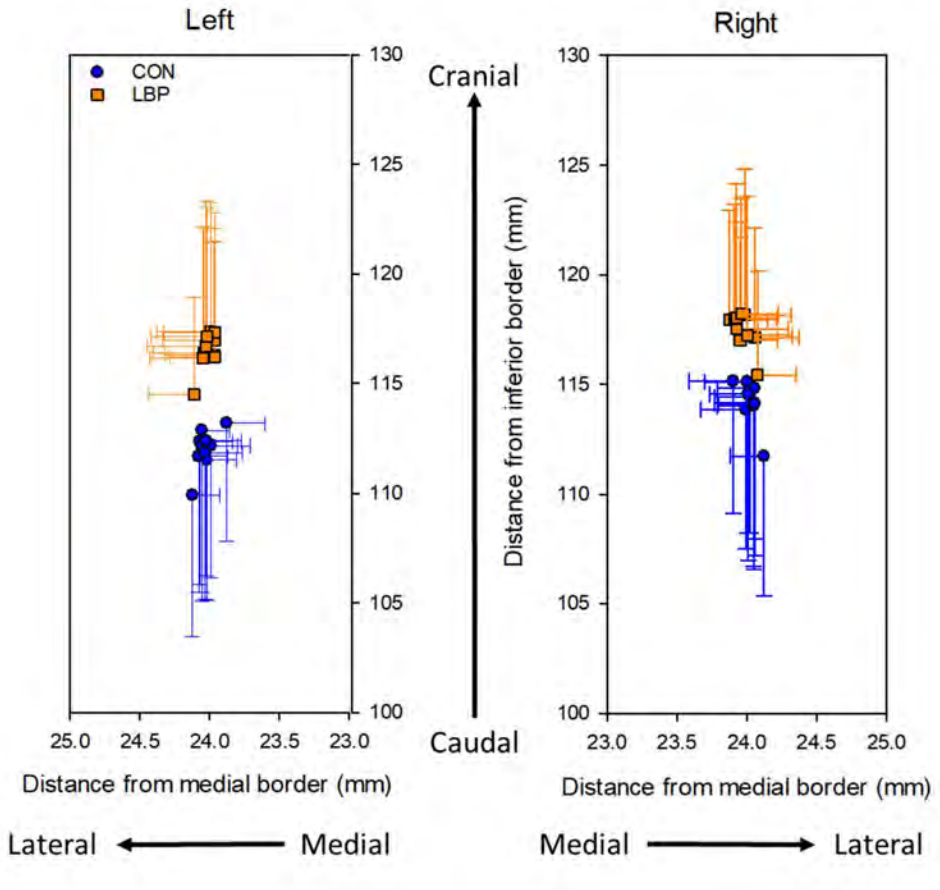


Fig. 5.5 – This figure indicates the absolute location of the centroid in the x and y axes throughout the task. In this figure, each shelf movement is identified by a single point indicating the mean centroid location for the movement across all cycles and participants.

Consistent differences in RMS were identified in data normalised to the first epoch for each side. Within this analysis, for each side, across all cycles for each movement, the LBP

group showed greater normalised muscle activity than the CON group. With muscles categorised as moving towards the ipsilateral or contralateral side for rotation, systematically greater muscle activity was identified in the LBP group for all movements and all cycles ($P<0.001$ for all; Fig. 5.6). This finding was also consistent for movements occurring only in the sagittal plane (S1-2 $P<0.0001$; and S2-1 $P<0.0001$), where muscles were working in an anterior direction.

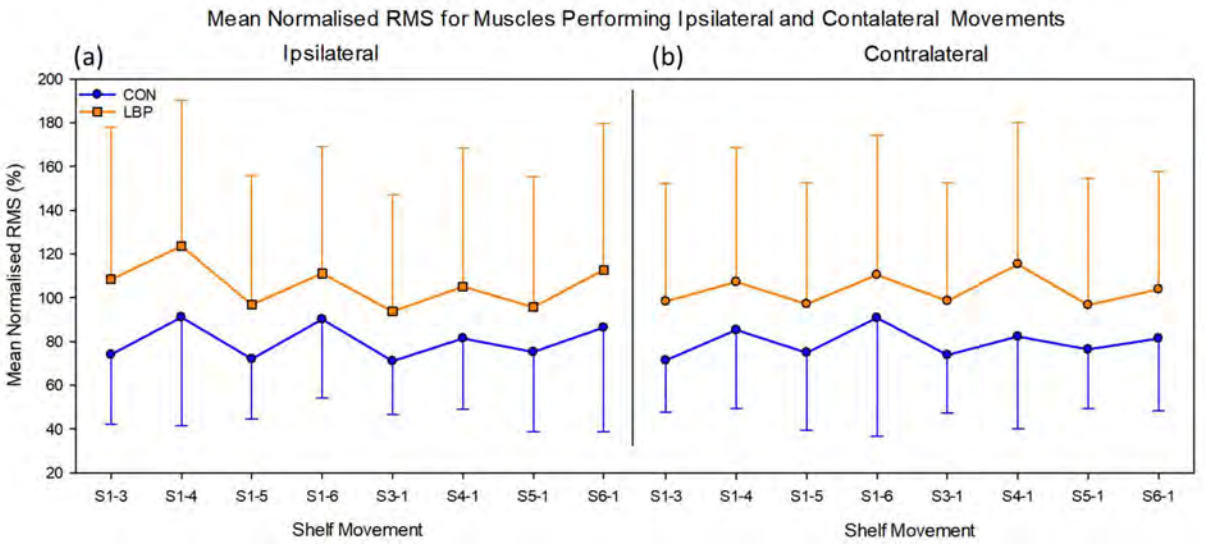


Fig. 5.6 – Normalised muscle activity for each movement in muscles moving in ipsilateral and contralateral directions to their anatomical location.

Significant differences were also identified in the entropy of the EMG amplitude map, across all cycles of all movements with sides assessed independently and combined ($P<0.034$ for all). In all iterations of this analysis, the CON group showed higher levels of entropy, indicating more homogenous muscle activity. This finding supports observed results from the topographical maps of muscle activity. The representative EMG amplitude maps illustrated in Fig. 5.7 indicate a more diffuse contraction for the CON group while the LBP group appeared to have a less homogenous contraction, with activation focussed cranially.

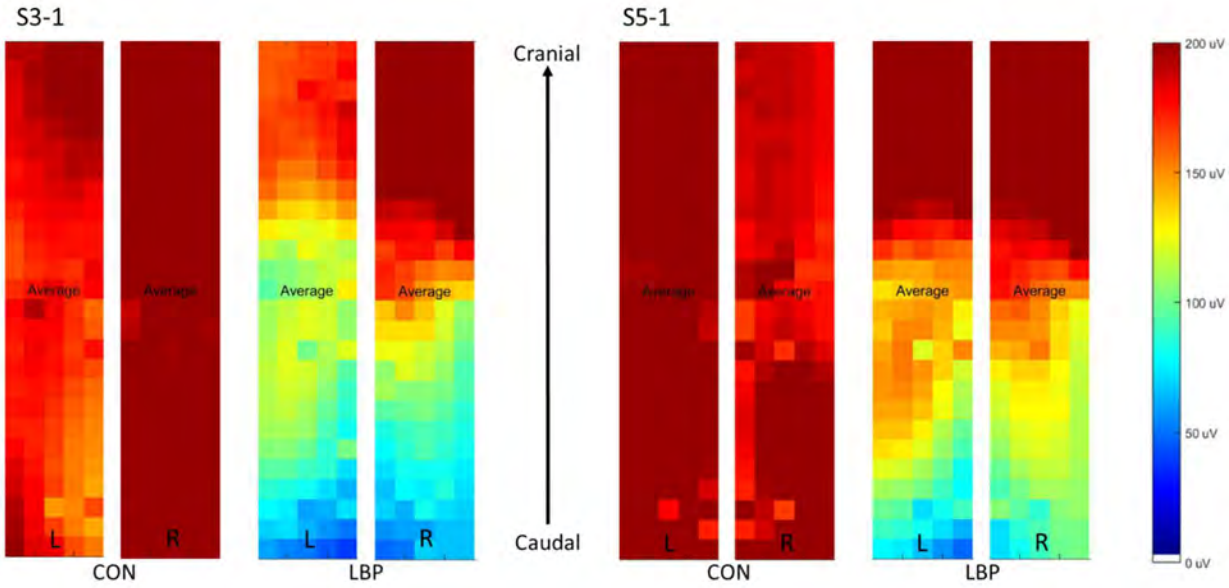


Fig. 5.7 – Representative maps of muscle activity for the distal to S1 aspect of the movement from S3-1 and S5-1. These maps indicate a more homogenous diffuse contraction in the CON group and a less diffuse and more cranially focussed contraction in the LBP group. They additionally show a differing distribution of the diffuse activity between movements for the CON participant.

5.3.3 – Kinematics Results

Systematic differences were identified between groups in the absolute 3-D movement patterns utilised to complete each movement ($P<0.05$ for all). However, when the data were normalised for the starting position of each participant, and the angular deviation between the lumbar and thoracic segments from this point was considered, few consistent meaningful differences were identified between groups (Fig. 5.8 – representative movement).

Within the normalised angular deviation data, when considering differences between groups for each movement (n=10) and in each axis (n=3), 20 outcomes of ANOVAs (*e.g.* LBP vs CON for S1-4, Y axis = one outcome) identified no systematic differences ($P>0.05$), with the remaining ten outcomes identifying systematic differences between groups ($P<0.05$). Of

these outcomes, seven identified differences were around the X-axis (frontal plane), one around the Y-axis (transverse plane) and two around the Z-axis (sagittal plane).

Around the X-axis, differences were identified within movements to S3 and S6, and in all movements returning to S1 from peripheral shelves ($P<0.05$ for all). The total range of deviation for both groups between the lumbar and thoracic segments for all movements in the X-axis was 4.9º (between 0.5º and 5.4º). Thus, all identified differences between groups related to movements of 5º or less. For each movement where differences were identified, the LBP group showed on average 0.7º greater deviation than the CON group.

In all movements around the Y-axis for both groups, the total range of deviation between segments was 13.7º (0.9º-14.6º). No differences were identified for most movements, however around this axis the CON group showed on average 1.19º more deviation between segments for the movement S6-1 ($P=0.007$). For this movement, differences were also identified between groups across cycles, with the CON group showing greater variation in the movement pattern than the LBP group ($P=0.022$). Differences in the movement pattern across cycles were also identified for the movement S4-1 ($P=0.019$). However, these were less consistent, with the LBP group showing greater deviation in initial cycles, and the CON group showing greater deviation in later cycles.

A total range of deviation of 13.3º (6.3º-19.6º) was identified around the Z-axis for both groups. Systematic differences in movement strategy were established around this axis for movements both to and from S5 ($P=0.024$, $P=0.006$ respectively). In both cases, the LBP group demonstrated greater deviation with an increase of 0.39º for S1-5 and an increase of 0.9º for S5-1 when compared to the CON group movement strategy. Around this axis, differences were also identified between groups across cycles for movements from S3-1 ($P<0.0001$). In initial

cycles, the CON group showed greater deviation for this movement, however in later cycles this was reversed and the LBP group showed greater deviation.

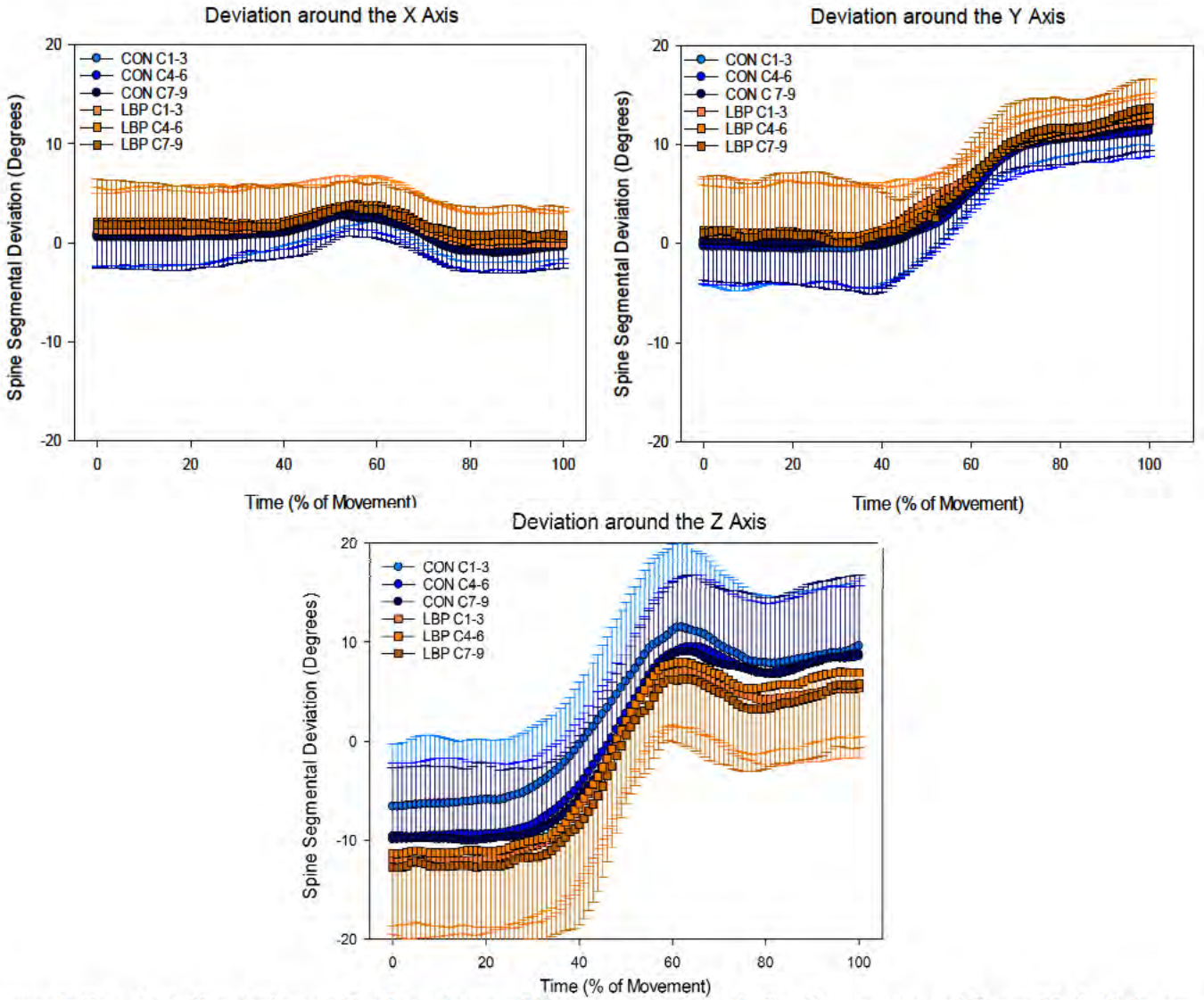


Fig. 5.8 – Representative deviation between the Lumbar and Thoracic Segments for the movement from S1-4. Data are shown for each group of cycles in (a) X, (b) Y and (c) Z axes

5.4 – Discussion

This study is the first to use HDEMG to assess the distribution of muscle activity across the lumbar and thoracolumbar regions during a multiplanar lifting task in people with mild-moderate CNSLBP. Regardless of the differing biomechanical stresses placed on the lumbar and thoracolumbar region by the complex multiplanar task performed in this study, participants in the LBP group used a consistent motor control strategy to complete all movements. This strategy appeared to be characterised by a less diffuse and more cranially focussed contraction of the ES, which showed less variation between sides across axial, sagittal and coronal movements. Despite these differences in muscle activation, there were few consistent differences in the movement strategy, indicating that the task was being completed in a similar manner, but using different regions of the ES. The task was designed to reflect a functional lifting task or a task of daily life, however with contrasting activation strategies it is possible that the continual activation of the same muscle region could influence the persistence of pain or fatigue in this region.

5.4.1 – Muscle Activity

The location of the centroid of the EMG amplitude map in the LBP group appeared to be less varied and more cranially focussed throughout the experimental task. In previous studies, there have been differences reported between groups in the overall variability in the centroid location throughout a task (Abboud et al., 2014, Falla et al., 2014). However, here no such variability was identified between groups, with the only differences occurring in the x-barycentre for sagittal plane cardinal movements. Instead, due to the 3-D and multiplanar nature of the task, variability was considered primarily between sides within groups. EMG is principally employed as a technique to assess the muscular activation created to produce a

movement, and in this task a variety of different movements were required (Merletti and Parker, 2004). Muscular coordination between sides is known to be essential to producing varied 3-D movements and has been studied extensively using bipolar EMG (Williams et al., 2013a, Willigenburg et al., 2013, MacDonald et al., 2010). While the neural drive to synergistic muscles cannot be implied from EMG amplitude alone (Martinez-Valdes et al., 2018), assessing the relative contraction characteristics of the left and right ES via the centroid location of the EMG amplitude map is a potential vector in which to understand the motor strategy employed in response to the varying task demands.

At points in the task which were proximal to S1, participants in both groups showed similar motor strategies between sides, as could be expected for a sagittal monopolar movement. However, at the points in the task distal to S1, the LBP group continued to show similar activation between sides whereas the CON group demonstrated clear differential activation of the ES in response to different task demands. These differences in the lateral distribution might have been explained by the overall variability of the centroid location, however as there were no differences between groups for most movements, instead it indicates that the LBP group activated the same regions of the muscle for all movements across the task duration despite the varied biomechanical demands presented. Similar patterns of continual activation of specific regions have been identified previously in studies investigating the influence of pain on muscle activity and this has been linked to increased localised fatigue and potential ischemia (Madeleine et al., 2006, Barbero et al., 2016, Abboud et al., 2014, Falla et al., 2014).

Across the duration of this task, as previously identified in Chapters three and four, the LBP group employed a consistently less diffuse and more cranially focussed contraction. This pattern of activation was again characterised in the systematically more cranial centroid and the

lower entropy of the EMG amplitude map, indicating a less homogenous contraction which was anecdotally identified in the topographical maps of muscle activity. As discussed in Chapter one, in order to produce movement, different regions of the ES work collectively (Bogduk, 2005, Macintosh and Bogduk, 1991), however this regional synergy appears to be diminished in people with CNSLBP, with reduced activation of the caudal ES. As all movements required elements of lumbar extension, it is thought that greater activation in the more caudal *iliocostalis lumborum pars lumborum* portion of the ES might be more biomechanically favourable given the increased shear forces on the lower lumbar vertebrae (Bogduk, 2005, Christophy et al., 2012). However, the cranial activation displayed here indicates a deselection of this region of the muscle in favour of the more cranial *iliocostalis lumborum pars thoracis* and *longissimus thoracis* regions. It is difficult to discern the impact that this activation pattern will have on lifting, as debate surrounds the concept of an 'optimum' lifting strategy (Nolan et al., 2018); however, the higher exertion indicated by Borg RPE responses following the task allows speculation that the LBP group strategy might require more effort and so be less favourable.

In contrast to other studies in this region, no differences between groups were identified in the gross variation of the centroid location in the y-axis across the duration of the task. Martinez-Valdes et al. (2019) reported a caudal shift of the Y-barycentre in a group of elite rowers with CNSLBP and a cranial shift in a control group, however the task in this instance was a repetitive rowing task which presents different biomechanical challenges to lifting and a dissimilar sample. Falla et al. (2014) reported a reduced variability in the Y-barycentre of the centroid for a CNSLBP group during a sagittal lifting task. However, in this instance, the task was a repeated movement to the same anterior shelf. Thus, differences between groups might have developed due to a shift of activation away from more localised fatigue due to the repeated nature of the task, rather than the cyclical task presented here (Falla et al., 2014).

Participants in the LBP group demonstrated greater normalised muscle activity across the task. This measure indicated that across all movements, while the CON participants reduced the magnitude of their contractions from the initial level of the first cycle, the LBP group maintained a greater contraction intensity throughout the task. This finding could support previous research which describes a reduction in movement of the painful area to protect the region from further injury (Jones et al., 2012, Hodges and Tucker, 2011, Shojaei et al., 2017b).

5.4.2 – Movement Strategy

While clear differences in the muscle activation strategy were identified, there were few consistent differences between groups in the manner in which the task was completed. The complex task was chosen to reflect occupational lifting or a task of daily living, however it is thought that the use of the metronome and the strictly timed movements prohibited too much variation in the movement strategy. Where differences were identified, generally the LBP group demonstrated greater deviation and this effect occurred at stages in the movement cycle when distal to S1 in the movement range. It is therefore possible that while the general strategy employed by the LBP group was similar to that of the CON group, reduced precision in 3-D movements as reported by other authors may increase spinal deviation at these points (Willigenburg et al., 2013). This is highlighted by the minor differences identified in the coronal plane, with increases in deviation of less than 1º which could be attributed to minor deviations, as it exceeds the approximate error of 0.1mm stated by the manufacturer (BTS Bioengineering, Milan, Italy). However, it is possible that these differences could be attributed to skin movement, which has previously been estimated to be between 5-7º for surface markers during gross movements when compared to radiographic images (Yang et al., 2008). As such, it is

possible due to the relatively small differences between groups, that these differences could be the result of skin movement artifacts.

Previous investigations have identified differences between groups in spinal ROM during lifting tasks (Falla et al., 2014, Shojaei et al., 2017a). However, the task used here was multiplanar and complex in nature, and required considerable concentration to maintain. Participants were allowed a practice cycle, however the overall consistency in the movement strategy might be due in part to the concentration required to maintain the correct pattern. Similar studies have reported reductions in the variability of spinal movements in participants with CNSLBP when completing cognitive duel tasks (Van Daele et al., 2010).

5.4.3 – Study Participants

The groups in this study were well matched, with no statistically significant differences between groups in sex, age, anthropomorphic factors or physical activity levels. However, as expected in a chronic pain population, the CNSLBP group reported lower physical and mental health and higher levels of disability, pain catastrophising and fear avoidance behaviours. These differences are not unexpected in a chronic pain population as signified by the biopsychosocial framework, which considers how chronic pain effects all areas of life (Turk and Monarch, 2018), however despite these differences, pain levels were relatively low. The sample was not under active management at the time of testing and so experienced lower levels of pain; on the day of testing the average level of CNSLBP within the group was 2.86/10, which is classified as mild (Breivik et al., 2008). However the group reported an average pain over the previous month of 5.93/10 which is at the higher end of the moderate pain classification (Breivik et al., 2008). While recruitment exceeded the sample size which was recommended for this study by the power analysis, the technical issues experienced forced a reduction in the sample size below

the recommended level and as such it is possible that this study was underpowered. This should be taken into account when interpreting the results of this study.

5.4.4 - Reliability

As in previous experimental Chapters, it is relevant to consider these results in the context of the reliability of HDEMG on the lumbar region in individuals with CNSLBP. As previously considered, this technique has not been previously be shown to be reliable in this population or context, so it has unknown consistency between uses which reduces the level of confidence in the findings in line with the GRADE criteria (Guyatt et al., 2011c, Guyatt et al., 2008).

In this instance, the interpretation of the results must also be considered in line with the small and very small effect sizes reported for each outcome (Lakens, 2013). It is thought that there could be several reasons for these small effects. One potential reason could be the loss of participants due to technical faults, which brought the recruitment number below the estimated threshold for adequate power (Turner et al., 2013). Additionally, it is possible that the effect sizes reported are conservative when compared to the actual effects. For the purpose of clarity and brevity, as stated in section 5.2.5, where each individual comparison within a group reported the same effect as the overall group result, only the overall group result was stated. As such, rather than reporting individual effects (one per shelf movement) which may have been greater, the effect size represented the combined effect of each comparison which reduced the size of the overall effect (Lakens, 2013). Nonetheless, as the reported effects were very low, the confidence in the reported effects must be reduced accordingly (Guyatt et al., 2011a). The cumulative effect of these factors alters the interpretation of these findings as there is very low confidence in the strength of the evidence in line with the GRADE interpretations. While it is

possible that the results presented herein have potential clinical applications, without reliability data to prove consistency in the outcome, it is currently not possible to adapt these results for clinical applications.

5.4.5 – Strengths and Limitations

This study is the first to show that directional specificity in how the lumbar paraspinal muscles activate to complete 3-D movements is diminished in people with CNSLBP. The use of HDEMG bilaterally across the lumbar and thoracolumbar regions allowed for a unique and complete characterisation of muscle activity across the lower back. The complex multiplanar task employed was reflective of occupational lifting tasks, and may allow insights into the provocation of pain. This study is reported in line with the STROBE statement, and it is anticipated that assessment with the NOS scale from Chapter two would find a low risk of biases in the methodology and reporting of this study.

The sample was broadly reflective of the combined characteristics of people experiencing mild to moderate CNSLBP who are still able to work and continue with tasks of daily life (Carlesso et al., 2018). As with the results of previous Chapters within this thesis, these results might not be generalisable to populations experiencing greater levels of pain, however, it is speculated that with greater pain the patterns identified here might be magnified (Arendt-Nielsen and Graven-Nielsen, 2008). Further research is therefore required to understand the relationship between muscle activation and graded pain levels. The motion analysis software automatically replaced deleted cycles with data from the subsequent repetition, so the decision to average across cycles was made in order to draw comparisons. However, this averaging has prohibited comparisons which might elucidated the differences in movement strategy identified to some shelves. It is suggested that further research in

populations with greater pain would be relevant to investigate the effect of symptom severity on the motor control strategy.

5.5 – Conclusions

In this study, participants with CNSLBP appeared to use a consistently less diffuse and more cranially focussed muscle activation strategy, which demonstrated fewer changes in the distribution of activity across movements. This strategy appeared to produce few differences in the movement strategy, however led to increased exertion across the task and might influence the persistence of CNSLBP symptoms. These differences in muscle activation may present opportunities for the development of novel rehabilitation for CNSLBP. Further research in this field should therefore investigate the potential for using the distribution of muscle activity to design a rehabilitation approach. One potential mechanism by which this could be achieved is through the use of biofeedback, as a means to facilitate individual understanding of how a participant activates their muscles.

CHAPTER 6

CAN NOVEL, HIGH-DENSITY ELECTROMYOGRAPHY FEEDBACK BE USED TO ALTER THE DISTRIBUTION OF MUSCLE ACTIVITY IN CNSLBP? AN EXPLORATORY QUASI-EXPERIMENTAL STUDY.

This study has not been previously published or presented in any form.

6 – Abstract

The results of Chapters three to five identified aberrant muscle activation distribution in the ES in people with CNSLBP which is not present in pain free controls. It is hypothesised that altering this distribution of activity in people with CNSLBP may influence the presence of symptoms. Previous studies have demonstrated that simple EMG biofeedback in people with CNSLBP can alter muscle activity and improve PROMs. Detailed biofeedback maps from HDEMG have been shown to encourage redistribution of muscle activity in healthy participants, but this has not been studied in a symptomatic population. This preliminary quasi-experimental study aimed to explore if detailed HDEMG biofeedback maps could influence the distribution of muscle activity in people with CNSLBP. Ten LBP participants (30.8 ± 12.8 years) with moderate CNSLBP (3.67 ± 2.19 /10) were recruited for this repeated-measures study. Two 32-channel HDEMG grids (4x8 electrodes) were placed on the most painful side of the lumbar and thoracolumbar ES to record muscle activity. Participants were asked to perform a 30s Ito extension and to correct their posture from a slumped seated position, then trained to use a colourised topographical map of muscle activity as biofeedback, before completing each task again; the protocol was then repeated in a second session. Participants were able to use the biofeedback to cause a 9.31mm caudal shift in the centroid of the EMG amplitude map in the postural correction task ($P<0.05$), and an increase in the RMS in the caudal region of the ES ($P<0.05$). Results for the Ito test were less conclusive, with an increase in RMS demonstrated ($P<0.05$), but no change in centroid location with biofeedback ($P>0.05$). While differences were identified in myoelectric outcomes, there appeared to be no change in pain or perceived exertion across conditions ($P>0.05$). These results suggest that detailed HDEMG biofeedback could be used to alter muscle activity in people with CNSLBP, however there appears to be no short-term change in PROMs.

6.1 – Introduction

Biofeedback is a tool whereby a biological response from the body is used as a form of feedback to the individual, giving people the opportunity to control processes which were previously considered involuntary (Frank et al., 2010). Bipolar EMG biofeedback has been used for many years for a range of rehabilitation reasons with results demonstrating reductions in pain and other PROMs, and improvements in muscle and joint function (Giggins et al., 2013, Huang et al., 2013, Terlikowski et al., 2013, Yılmaz et al., 2010). In the lumbar region, bipolar EMG has also been used as a means to modulate muscle activity in people with CNSLBP, and while reductions in muscle activation have been identified, few studies have identified a reduction in CNSLBP symptoms (Sielski et al., 2017, Jones and Wolf, 1980, Neblett, 2016, Stuckey et al., 1986).

More recent studies have used HDEMG biofeedback on the *trapezius*, using the amplitude of the signals as the means to provide feedback in healthy populations (Samani et al., 2010, Gaffney et al., 2016). To create the feedback in these instances, the studies averaged the amplitude of signals across the cranial and caudal regions of the HDEMG grid to create cranial/caudal contraction ratios. Biofeedback was given in the form of a light flash if the ratio moved outside of a given range that indicated to participants that they should alter their contraction (Gaffney et al., 2016, Samani et al., 2010). However, this form of biofeedback is binary in nature and offers very little guidance on how the contraction could or should be altered. Arvanitidis et al. (2019) used HDEMG to display detailed real-time colourised topographical maps of *trapezius* muscle activity in a healthy population, allowing participants a visual means to identify and understand the distribution and focus of their muscle contraction. In the biofeedback condition, participants were able to demonstrate increased redistribution of

muscle activity throughout the course of the endurance contraction compared to no biofeedback. However, there was no statistically significant difference in task performance (*e.g.* the time to task failure between conditions), potentially due to the restrictive conditions of the task (Arvanitidis et al., 2019) and that the study was conducted on a small sample of asymptomatic people. Nonetheless, the increased redistribution of the centroid of the EMG amplitude map has demonstrated that this form of detailed biofeedback can alter the muscle activation in healthy participants, however further research is required in symptomatic populations.

As reported in Chapter three, during static endurance tasks people with CNSLBP demonstrated lower activation of the ES, paired with a more cranial distribution of activity (Sanderson et al., 2019b). Similar studies have also previously identified more restricted dispersion of activity in people with CNSLBP during static endurance tasks (Abboud et al., 2014). Similarly, during monoplanar dynamic lifting tasks, people with CNSLBP demonstrated less redistribution of ES activity during a fatiguing task (Falla et al., 2014) and greater activation in more cranial lumbar and thoracolumbar regions (Chapter four) (Sanderson et al., 2019a). This pattern of activity was also demonstrated during a multiplanar task in Chapter five, where people with CNSLBP also appeared to be less able to vary the muscular activation in the ES to cope with changing biomechanical demands. A pattern of activation which was both cranially focussed, and demonstrated less variation between sides was identified throughout this task.

The evidence put forth from these studies indicates that people with CNSLBP display an aberrant pattern of muscle activation. The work in this thesis has characterised this activation in the ES as less diffuse and more cranially focussed, in contrast to diffuse and more centrally focused activation in control participants. Within the vicious cycle framework for understanding chronic pain, it is thought that pain causes individuals to adapt and change the

way in which they move, this adaptation places new biomechanical strains on the individual which in turn can cause further pain (Roland, 1986, Hodges and Tucker, 2011). The collated evidence from previous Chapters within this thesis suggests that the altered distribution of muscle activity may represent one such adaptation to CNSLBP although it is not possible to infer causation from the studies conducted. Nevertheless, it may be possible that using biofeedback to facilitate a change in the distribution of muscle activity in individuals with CNSLBP to incorporate increased activation of the caudal ES could form the basis of a novel intervention which ultimately could change symptoms.

This study aimed to explore the possibility of using this form of detailed HDEMG biofeedback to alter the distribution of muscle activity which has been identified in people with CNSLBP throughout this thesis.

6.1.1 – Objectives

The objective of this prospective study was to explore the use of HDEMG biofeedback maps of lumbar and thoracolumbar ES activity to facilitate the activation of caudal regions of the ES in CNSLBP participants and further to investigate the immediate influence of this biofeedback on PROMs.

6.1.2 – Hypotheses

H6.1 - It was hypothesised that before biofeedback training, people with CNSLBP would initially show the same cranially focussed and less diffuse distribution of muscle activity as described in previous Chapters.

H6.2 - It was also hypothesised that these participants would be able to use the colourised HDEMG biofeedback maps to alter the spatial distribution of muscle activity in the ES.

H6.3 - It was hypothesised that if this alteration in the distribution was possible, then there would be a reduction in negative PROMs (e.g., reduction in pain symptoms).

6.2 – Methods

This study reports preliminary results from a single arm of a quasi-experimental exploratory study using a repeated measures design. Data collection was conducted at a laboratory within CPR Spine, University of Birmingham. Recruitment and data collection for this study was completed between October 2019 and February 2020 and data were collected across two sessions for each participant. Ethical approval for this study was granted by the University of Birmingham Ethics Committee (ERN_18-1261A, Appendix 11). Participants gave written informed consent prior to data collection and all procedures were completed in accordance with the Declaration of Helsinki.

6.2.1 – Participants

People with CNSLBP were recruited in the same manner, and using the same inclusion and exclusion criteria, as described during Chapters four and five. Due to the exploratory nature of this study, an *a-priori* power analysis was not conducted to inform sample size. Instead, this study was conceived to test the concept and collect pilot data in this population which could inform future study sizes.

6.2.2 – Questionnaires

As in previous Chapters, participants completed baseline questionnaires prior to the experimental tasks, in order to characterise the sample. As this study was not linked to any other studies (as was the case in Chapters four and five) the outcome measures closely reflect those

used in Chapter three. In this instance, these questionnaires include the custom CNSLBP questionnaire (used in Chapters four and five), the IPAQ, ODI and the TSK. Additionally, beliefs surrounding the participants' ability to alter their muscle activity, and the influence that this would have on pain, was assessed using a modified version of the Pain Self-Efficacy Questionnaire (PSEQ; Appendix 12) (Bandura, 2006, Nicholas, 2007). This measure was intended solely to explore the participants self-efficacy to adapt their muscle activity in biofeedback, and how this changed following biofeedback training and so is not validated or assessed for reliability. This tool used a 0-100 response scale representing a range from 'Cannot do at all' to 'Highly certain can do' to assess self-efficacy in two domains, altering muscle activity (Nicholas, 2007), and reducing pain (Bandura, 2006). All questionnaire data were collected and managed using REDCap electronic data capture tools hosted at the University of Birmingham (REDCap consortium, Vanderbilt University, Nashville, TN, USA).

6.2.3 – Experimental Task

This study used a repeated measures design and comprised two sessions spaced 18-48 hours apart, exploring the use of biofeedback as an intervention. This design allowed for both within- and between-session comparisons of muscle activity, and to explore if any effects could be sustained following a short washout period between sessions. In the first session participants completed the questionnaires before proceeding to the four experimental tasks, split by a biofeedback training session. In the second session participants proceeded directly to the three experimental tasks (Ito test only with biofeedback) with biofeedback re-introduced between task one and two (Fig. 6.1). The procedures were developed with input from the CPR Spine

Patient and Public Involvement panel. Members from the panel were asked for tasks which caused an exacerbation of their CNSLBP symptoms and the tasks were modelled around these.



Fig. 6.1 – Flow chart demonstrating the progression of tasks within sessions. Biofeedback initiation is marked by orange chevrons, no task prior to these points was facilitated by biofeedback.

6.2.5.1 – Session One

Following baseline questionnaires, the session commenced with a 30s Ito lumbar extension test, in the same manner as described in Chapter Three (Ito et al., 1996, Sanderson et al., 2019b). Participants were first given a demonstration of the position and task by a researcher, and then allowed one practice contraction of 3-5s to ensure the correctness of the technique.

Participants were then moved to backless stool, the stool was a constant height to better reflect seating in a typical uncontrolled environment, but participants were able to rest their feet on the floor or the stool's foot-rest to ensure that their position was stable. Participants were asked to look towards a computer screen one metre anterior to the stool and to relax anteriorly into a natural, slouched posture. From this position, participants were asked to perform three postural corrections at a self-selected speed. To complete the task, participants were asked to sit up straight, but no further guidance on technique was given (Falla et al., 2007). Participants were told when to start the movement and asked to signal when they had reached their chosen upright position, three repetitions of this task from the slouched position were performed.

At this stage, participants were given biofeedback-enhanced postural correction training, using the real-time coloured visualisation of topographical muscle activity (colour map; monopolar interpolated signals; bp Meacs, LiSiN, Turin, Italy). The anterior computer screen was used to show the colour maps and an explanation of the visual display was given to participants (Arvanitidis et al., 2019). Moving tactile pressure was placed on the grid from top to bottom to show how the map was topographically distributed and participants were encouraged to contract the ES to understand how their activity was visualised. When participants were comfortable in their understanding of the colour maps, a musculoskeletal physiotherapist with five years of experience gave specific training on how to complete a postural correction (Falla et al., 2007). During this training, the colour map was used as an aid to visualise the muscle contraction and supplement the physiotherapist advice. Based on previous work in this thesis that people with CNSLBP preferentially activate more cranial regions of the ES (Sanderson et al., 2019a, Sanderson et al., 2019b), specific emphasis was placed on ensuring that participants focussed activation in more caudal regions. When the physiotherapist was satisfied that the participant was able to perform the movement correctly, and the participant was confident that they were able to use the biofeedback to activate different regions of their back musculature, the task proceeded.

The participants were then asked to perform three further postural corrections, using the biofeedback as a guide. In these movements, participants were asked to complete the movement they learned during the physiotherapist training, and use the map to ensure maximal activity in the caudal regions. Three repetitions were performed of this task in these conditions.

Finally, a second 30s Ito test was performed with the aid of the biofeedback, with the screen placed below the plinth in a position visible to the participant during the task. During

this contraction, participants were encouraged to maintain the same position but focus activation more caudally throughout the task, and aim to maximise activation in this region.

After each experimental block, participants were asked to rate how difficult they found the task using the Borg RPE scale (Borg, 1998), and their back pain during the task using a PNRS scale displayed on an iPad through REDCap. At the end of the testing session, following their experience with the biofeedback tool, participants were asked to again complete the modified PSEQ as a post-session comparison.

6.2.5.2 – Session Two

At the start of the session, the PNRS was used to measure the level of pain at baseline for session two. Using the same experimental set-up, participants first completed three postural corrections without visual biofeedback or further training, they were encouraged to use the techniques learned in the previous session and to maximise activity in the caudal region. This stage was designed to assess how well participants had retained the training without the biofeedback display following a short washout period. Participants were then displayed the topographical colour maps and were allowed to practice independently to re-familiarise themselves with the biofeedback without any further training or researcher input. When participants were ready, the tasks were repeated from the second half of session one, with three postural corrections with biofeedback, and a 30s Ito test with biofeedback. As in session one, participants rated their exertion and pain following each block of testing.

6.2.4 – Experimental Set-Up

6.2.4.1 – Electromyography

Two semi-disposable 32 channel HDEMG grids (8x4) were placed unilaterally over the ES muscle on the side in which participants experienced the greatest CNSLBP symptoms. The grids were prepared by first affixing one continuous custom double-sided adhesive foam pad to both grids (LiSiN, Turin, Italy), functionally creating one 64 channel grid (16x4), with a constant 10mm IED. These grids were prepared and affixed to prepared skin, starting at a point 2cm lateral to the L5 spinous process, in the same manner as described in previous Chapters. The 2cm distance from the spinous processes was maintained for the upper grid, and confirmed at the T12 level via palpation and skin marking (Fig. 6.2). Reference electrodes were placed on the 2nd and 4th lumbar vertebral spinous processes. The skin was marked using a non-erasable surgical skin marker around the grid during session one to ensure identical placement during session two.

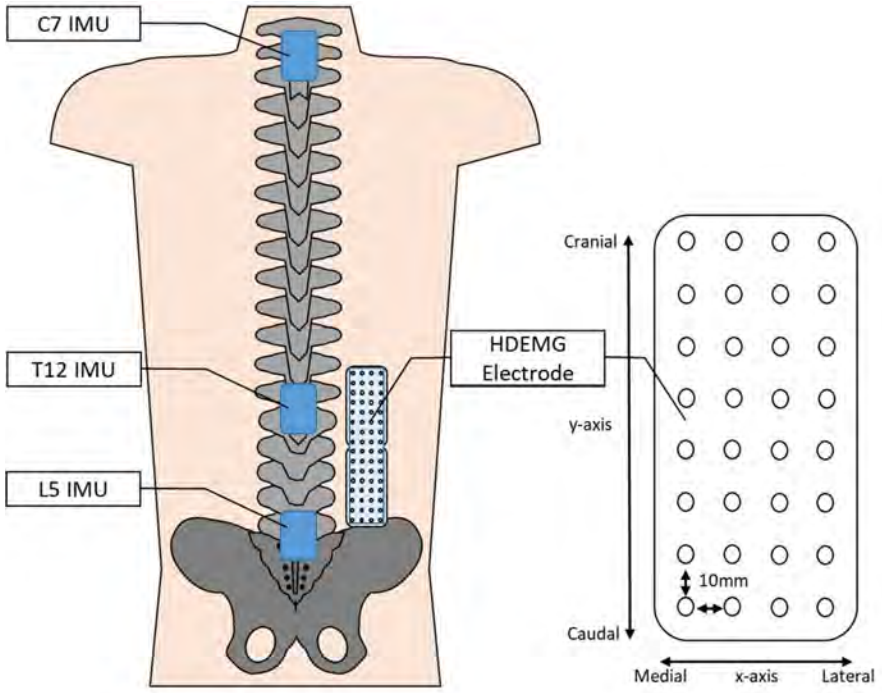


Fig. 6.2 – A schematic of the experimental set-up, demonstrating the location and design of the HDEMG grids joined by a single constantly spaced pad. Also shown are the inertial motion units (IMUs) over the spinous processes of the C7, T10 and L5 vertebrae (not to scale).

EMG signals were sampled at 2048Hz and recorded via two wireless HDEMG amplifiers (Meacs, LiSiN/OT Bioelettronica, Turin, Italy). This HDEMG system was chosen for use in this study as it is small, lightweight, wireless and can process and display colourised feedback maps in real-time (Cerone et al., 2019). A gain of 192 was applied and signals were converted with a 16-bit analogue to digital converter. Signals from each 32-channel grid were collected through independent wireless amplifiers, connected through a Wi-Fi network, and were recorded with a maximum delay between units of ±500μs. A synchronisation signal, from the kinematics system (described below) was collected on a 33rd channel of both amplifiers and all signals were recorded and saved for offline processing.

When displaying real-time colour maps of muscle activity, signals were displayed topographically (with respect to their position on the grids) through manufacturer software, processing was applied automatically (bp Meacs, LiSiN, Turin, Italy). Each monopolar signal was rectified to produce monopolar RMS values for each point, and plotted using a colourised scale of activity, with regions of lower activity shown as blue regions and greater muscle activity shown as red (example, Fig. 6.3). When displaying these topographical colour maps of activity, signals were interpolated for display purposes and refreshed at epochs of 0.1s (Arvanitidis et al., 2019, Falla et al., 2007). As analysis was performed offline, and normalisation to MVC was not possible for this colour-mapping, there was no validated reliable technique which could be used to scale the visualisation. Thus, the grid was scaled subjectively for each participant during the training sequence, to ensure that the scale was sufficient to visualise activity. Typically, this involved a range of 0-100μV for the seated tasks and 0-300μV

for the extension task, however this was slightly adjusted as required and then maintained to the same scaling for each participant over subsequent repetitions.

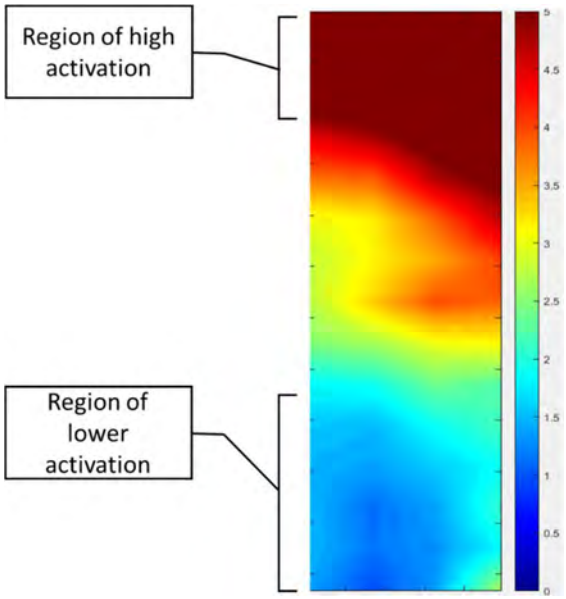


Fig. 6.3 – Example of a colour map displayed to participants, with regions of greater activation shown in red, and lower activation in blue.

The EMG data were analysed using custom code on MatLab (The Mathworks Inc., Natick, MA, USA) as described in previous Chapters. In addition to this processing, regions of the large grid were isolated in order to assess the regional distribution of activity. These regions were topographical, with 4x4 signals comprising a region, as such upper, upper-middle, lower-middle and lower regions were created (from superior to inferior).

6.2.4.2 – Motion Analysis

Kinematic data on the range of spinal movement was collected using wireless inertial motion units (IMUs) from the Noraxon MyoLab (Noraxon, Scottsdale, AZ, USA). This method of kinematic data collection was selected for this study in lieu of the optoelectronic system due

to its portability and relative ease of use. IMU sensors were adhered to the skin overlying the spinous processes of the C7, T12 and L5 vertebrae using adhesive foam and secured with tape, in accordance with the manufacturer's guidance (Fig. 6.2). The placement of these sensors was such that the relative movements of the lumbar and thoracic spinal segments could be measured. In order to accurately quantify these movements, the distance from the C7-S1 vertebrae was measured. After placement of the IMUs, the system was calibrated with the participant in a quiet sitting position, with participants sitting still and looking anteriorly with feet supported and hands placed on their lap. Three-dimensional kinematic data from the IMUs were sampled at a rate of 100Hz and recorded for offline analysis using the Noraxon MR3 software (Noraxon, Scottsdale, AZ, USA). Alongside this data, a trigger signal from the Noraxon Myosync unit was recorded to enable synchronisation with the HDEMG signals (Noraxon, Scottsdale, AZ, USA).

6.2.5 – Statistical Analysis

Preliminary statistical analysis was completed using Statistica Version 13.3 (Tibco, USA), with an alpha level set at 0.05. A majority of collected data were normally distributed, but some demonstrated slight skew and/or kurtosis, however as this study is exploratory in nature statistical analysis should be interpreted as preliminary. Thus, statistical tests in this study are primarily intended to demonstrate if a relationship appears to be present or not, as such effect sizes have not been reported.

6.2.5.1 – Participant Characteristics

The baseline questionnaires were scored as in other Chapters, and this data were used to characterise the sample (Fairbank and Pynsent, 2000, Miller et al., 1991, Craig et al., 2003). Measures of self-efficacy were exported as values from 0-100 for both the pre- and post-session measurements. Any changes in self-efficacy over the session were identified using a dependant samples t-test with conditions of pre- and post-session.

To test H6.3, the reported scores for RPE and pain after each block of testing were assessed for statistically significant changes using repeated measures ANOVAs with conditions of pre- and post-feedback and session (1 or 2). All repeated measures ANOVAs were confirmed using Bonferroni and Newman-Keuls post-hoc tests where appropriate.

6.2.6.3 – Motion Data

The kinematic data were processed automatically within the Noraxon MR3 software (Noraxon, Scottsdale, AZ, USA) IMU optimised Kalman filters were applied to the raw data as described by Berner et al. (2020) and anatomical angles were reported for lumbar and thoracic flexion. Within the software, an experimenter marked the data to identify the start and end of each movement. The range of motion (ROM) was calculated by subtracting the minimum value within the marked region from the maximum value. Differences in the ROM were identified using repeated measures ANOVAs, with factors of day (session one/session two) and condition (no biofeedback/biofeedback).

6.2.6.2 – Muscle Activity

For the postural correction task signals were temporally averaged across the duration of the movement, in order to create a single value for each repetition per participant in each feedback condition. No differences were identified within reps; therefore, the three reps were averaged for further analysis. In order to test H6.1 and H6.2, these values were compared with repeated measures ANOVAs with factors of day (session one/session two) and condition (no biofeedback/biofeedback). For regional activation, each region (upper, upper-middle, middle-lower and lower) was compared with student t-tests across the experimental conditions.

The Ito test data were cut into 5s epochs, and temporally analysed, there were no significant differences across epochs so data were averaged across the duration of the contraction. To further test H6.1 and H6.2, these data were analysed using repeated measures ANOVAs with factors of day (session one/session two) and condition (no biofeedback/biofeedback).

6.3 – Results

6.3.1 – Participants

Ten participants with CNSLBP, including seven females and three males aged 30.8 ± 12.8 years, participated. At baseline for session one, the group presented with a mean (±SD) pain level of 3.67 ±2.19/10 for session one and 2.72 ±2.02/10 for session 2. A majority of the sample (66%) reported high levels of physical activity on the IPAQ questionnaire, with the remainder reporting moderate levels (n=9; data for one participant was incomplete for this questionnaire). Participants reported a mean disability of 17.04 ± 6.11% on the ODI and a score of 36.2 ± 4.8 on the TSK (Table 6.1).

Characteristic		LBP (n=10)
Age (Years)		30.8 ± 12.8
Sex (# Males)		3 Male
BMI		24.65 ± 3.2
IPAQ		66% High [A]
ODI (%)		17.04 ± 6.11
TSK		36.2 ± 4.8
Pain Characteristics	**Current Pain (S1)**	3.67 ± 2.19
	Current Pain (S2)	2.72 ± 2.02
	Most Painful Side	6 Right /4 Left
	Average Pain (4 Weeks)	4.96 ± 2.47

Table 6.1 – CNSLBP participant characteristics, unless otherwise stated all results are mean and SD. The IPAQ scores reflect the proportion of participants who scored high levels of activity. [A] – Data for one participant were incomplete, so this participant was excluded from this score.

6.3.2 – Subjective Outcome Measures

Each question in the PSEQ was assessed individually, and of 19 questions only one statistically significant difference was identified between the pre- and post-session measures. Participants showed significantly greater confidence that they would be able to use physiotherapist feedback to change how they use their muscles (Q7), with a mean increase of 21 ± 19.53/100 (P=0.0079). There were no other statistically significant differences between pre- and post-session measurements for this outcome (P>0.05 for all). Accordingly, the intervention demonstrated no difference in participants' perceptions of pain or exertion following each task. There were no differences in pain or RPE scores within sessions (pre- and post-feedback) or between sessions for either task (P>0.05 for all outcomes).

6.3.3 – Muscle Activity

6.3.3.1 – Postural Corrections

Prior to any training or guidance, participants used a postural correction strategy with a barycentre in the y (cranio-caudal) axis 91.92 ± 9.77mm cranial of the inferior margin of the grids. Following the biofeedback training session, the Y-barycentre of muscle activity was 82.61 ± 7.67mm cranial of the base of the grids, an average of 9.31mm more caudal (P=0.0097; Fig. 6.4). This effect was sustained in the second experimental session, with Y-barycentre locations of 84.08 ± 9.25mm (no biofeedback) and 83.04 ± 9.09mm (with biofeedback) cranial of the base. Using post-hoc tests, it was confirmed that the Y-barycentre location pre-training was significantly more cranial than all other conditions (P<0.02; Fig. 6.4). This redistribution of activity could be observed in the topographical maps of muscle activity (Representative

Maps – Fig. 6.5). The Y-barycentre location did not differ between any condition following the training session ($P<0.05$ for all). There were no differences in the location or the change in location of the X-barycentre at any point during the task ($P>0.05$ for all).

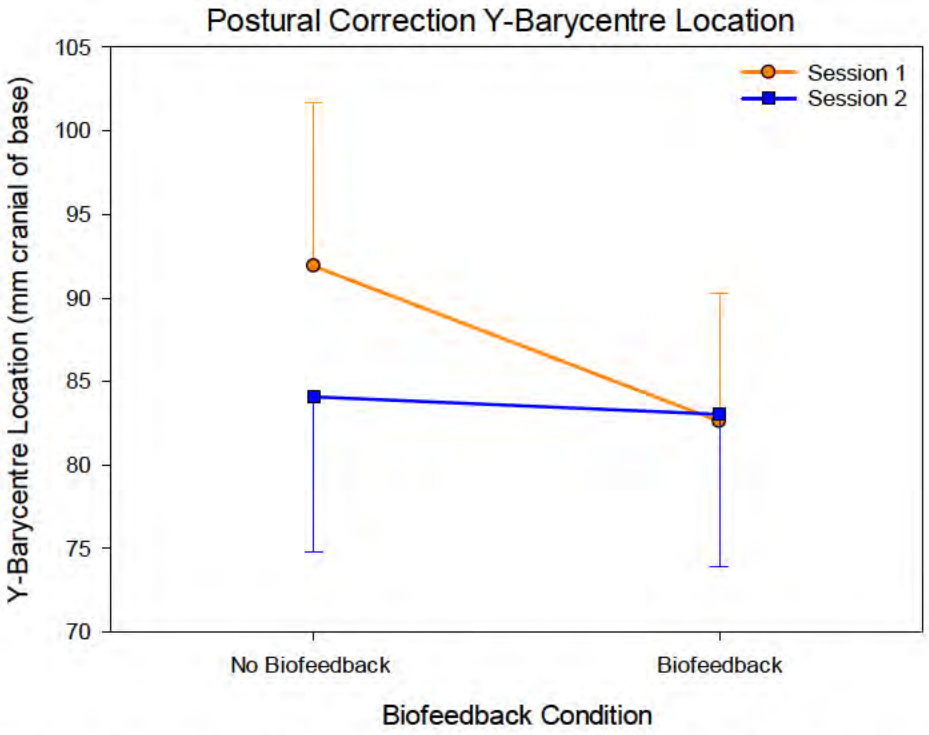


Fig. 6.4 – The location of the Y-barycentre in the cranio-caudal axis in biofeedback and non-biofeedback conditions across both sessions.

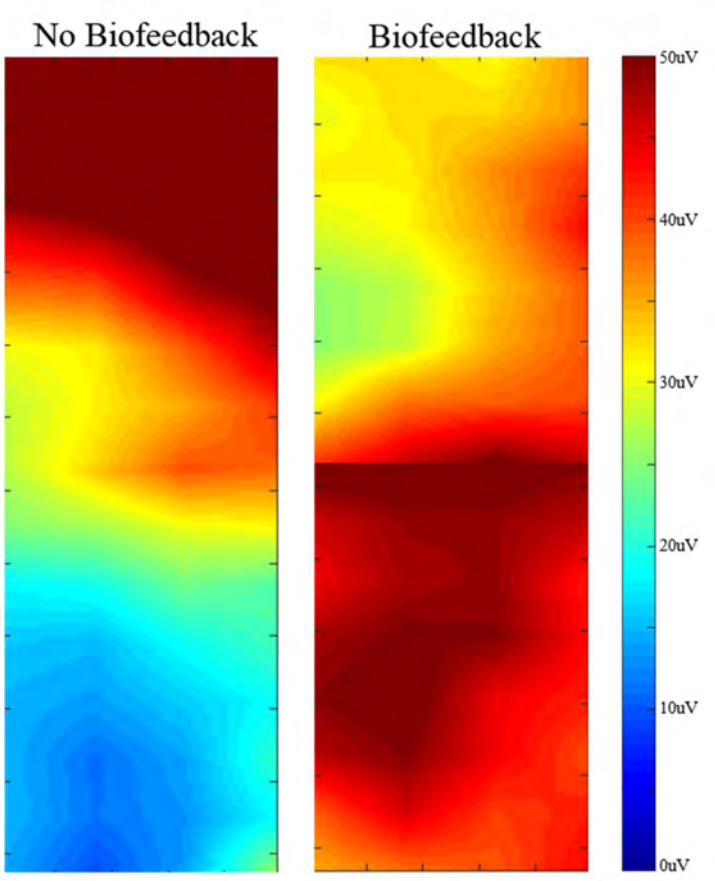


Fig. 6.5 – Representative topographical maps illustrating the redistribution of muscle activity during session one following the biofeedback training

The absolute magnitude of the RMS across the combined gird was not affected by the biofeedback training, and no differences in activity levels were identified within sessions for either day ($P>0.05$). There was a between sessions effect, with systematically greater muscle activity identified during session two ($P=0.021$). While the overall muscle activity remained consistent within sessions, the subdivided grid gave insight into the changing distribution of activity, with altered regional distribution identified in the biofeedback condition ($P=0.0036$). Activity in the regions within the lower grid showed an increase following the biofeedback training, with individual pre-post comparisons highlighting significant increases in muscle activity for the lower and lower-middle regions ($P=0.0054$, $P=0.006$ respectively). There were

no significant differences in the level of activity within the upper grid (P>0.05 for both upper-middle and upper regions; Fig. 6.6).

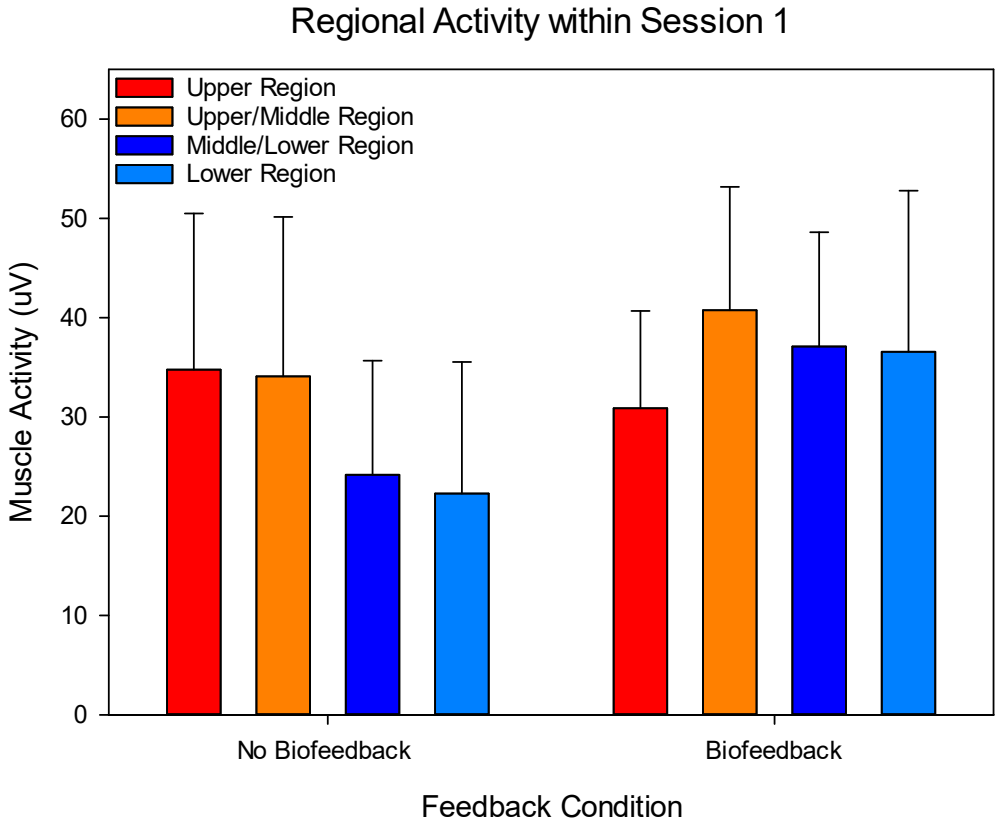


Fig. 6.6 – Demonstrating the regional activation within the large electrode grid between conditions within session 1. Note, the topographical distribution of the legend is representative of the topographical distribution of the regions of the grid from cranial to caudal.

In order to further assess the influence of biofeedback, the mean entropy in both biofeedback conditions (Session 1 and 2) was compared to values from the pre-feedback condition in both sessions. In this analysis, an increase in entropy was identified across the grids in the biofeedback conditions. The mean entropy in the pre-feedback conditions across both days was 5.58 ± 0.16, in the biofeedback conditions this increased to an average across days of 5.64 ± 0.14 (P=0.036). This finding was consistent when grids were considered independently

and combined, with greater entropy consistently identified in the biofeedback conditions (P=0.008). However, there were no differences in entropy within individual sessions for pre- and post-biofeedback conditions (P>0.05 for all).

6.3.3.2 – Ito Test

There were no differences identified in the topographical location of the centre of muscle activity between the pre- and post-biofeedback conditions (P>0.05 for all). The Y-barycentre in the pre-biofeedback condition was 86.79 ± 4.7mm cranial of the base of the grids, and following biofeedback training the location was 87.38 ± 5.04mm in session one and 88.53 ± 4.01mm cranial in session two (Fig. 6.7). Similarly, the X-barycentre and the entropy of signals across the grids demonstrated no significant differences across conditions or between days (P>0.05 for all).

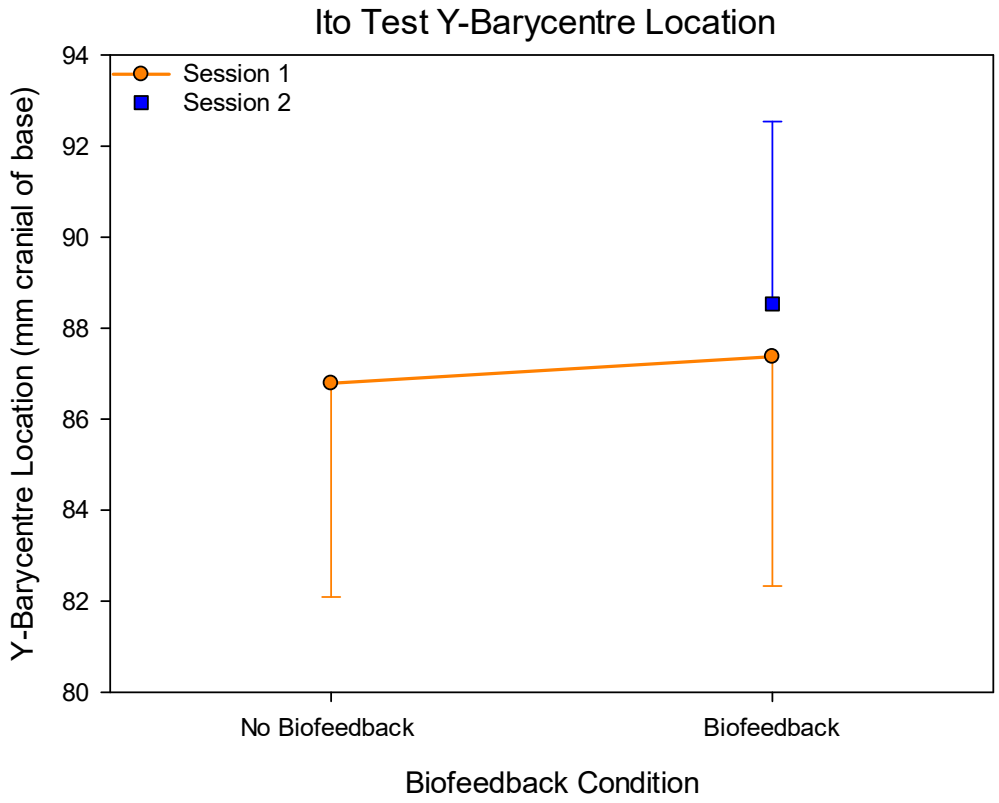


Fig. 6.7 – Location of the Y-barycentre in the cranio-caudal axis for the Ito Test in both biofeedback conditions. The Ito test was only conducted under biofeedback condition during session 2.

The RMS of the grids was affected by the biofeedback training during the Ito tasks, with an increase in magnitude of activity across the grids shown in the presence of biofeedback ($P<0.0001$). Bonferroni post-hoc corrections revealed that the levels of activity recorded during both biofeedback sessions were greater than the pre-training condition ($P=0.021$, $P=0.0005$ respectively), but not significantly different to each other ($P=0.26$).

6.3.2 – Kinematics

For the postural correction task, there was a mean increase in lumbar ROM of 7.4^{o} between the pre-training and all post-training conditions ($P<0.032$), however there were no differences between any post-training ROMs ($P>0.05$ for all, Fig. 6.8). There were no differences in thoracic ROM in any condition, pre-or post-training ($P>0.05$ for all). For the Ito task, there were no significant differences in lumbar or thoracic ROM for any condition in either session ($P>0.05$ for all).

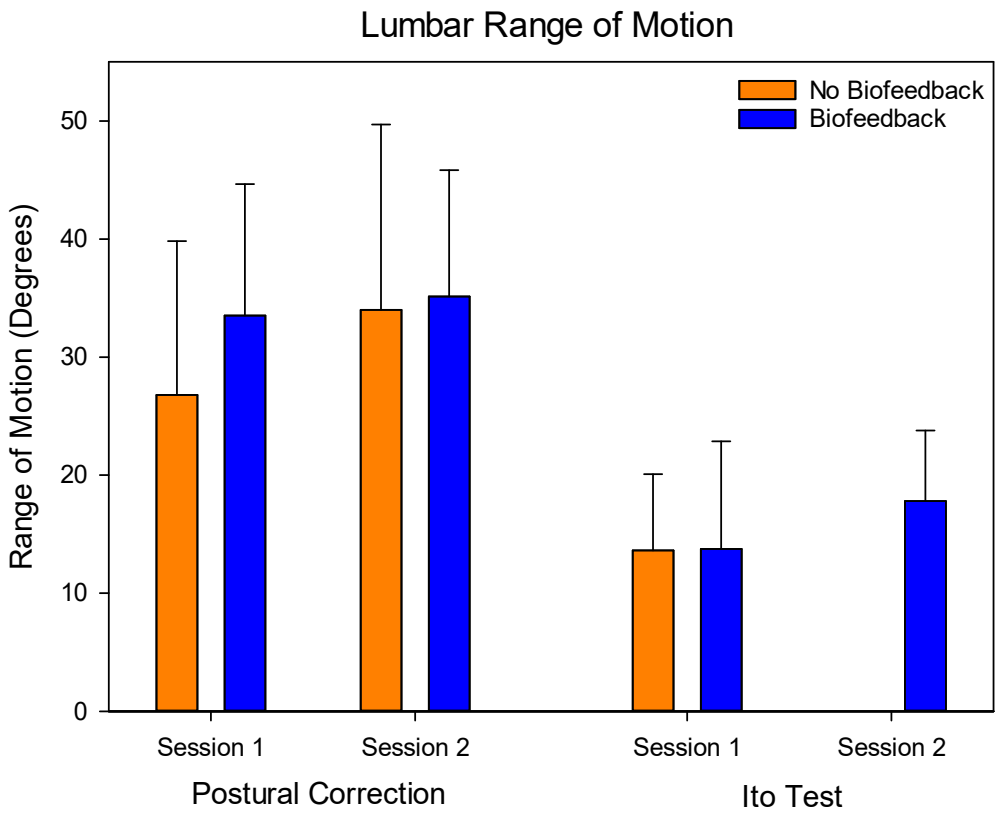


Fig. 6.8 – Depicting the mean lumbar range of motion in each condition across sessions

6.4 – Discussion

The results of this exploratory study indicate that detailed biofeedback can be used in people with CNSLBP to alter the distribution of muscle activity. Furthermore, participants were specifically able to alter the distribution of activity to activate the more caudal regions of the ES. However, as with other similar studies, there were no short-term differences identified in PROMs such as pain or exertion.

The results from this study suggest that participants were able to significantly alter their muscle activity when using the biofeedback maps of muscle activity. In the pre-training condition, participants initially utilised an activation strategy which has been described previously in each study within this thesis (Sanderson et al., 2019a, Sanderson et al., 2019b). This muscle activation strategy was characterised by a more cranially focussed and less diffuse spatial distribution of activity. This pattern of activation was identified during the postural correction task; muscle activity was focussed in the more cranial thoracolumbar region, in contrast to the diffuse activation usually demonstrated by CON participants. However, following the biofeedback training, this activity was redistributed caudally, with a substantial (9.31mm) shift in the Y-barycentre. Furthermore, while this shift was maintained in the pre-feedback condition of session 2, there was an overall more diffuse activation across the biofeedback conditions, indicated by increased entropy. This result was supported by the regional activity measures, which showed increased activation of the lower regions of the ES in the post-training conditions; not seen in the upper regions. This combination of more caudal and diffuse activation more closely mimics the activity of the CON participants in previous studies within this thesis during different tasks.

The changes to the distribution of muscle activity with biofeedback were less consistent in the Ito test component, with no differences identified in the topographical distribution of activity. This might indicate that the training technique allowed for task-specific adaptations, whereby the desired outcome was learned only for the sitting task, and the results were not transferable to the Ito task (Hubbard et al., 2009). However, in order to fully assess this possibility, a further task should have been completed in order to ascertain if the training was task specific, or did not translate to the Ito task specifically. Nonetheless, during the Ito test there was an increase in the overall RMS during the task, indicating that participants were able to focus and increase activation across the entire lumbar and thoracolumbar region. This increase in activity was produced with no significant changes in the kinematics of the movement, with similar ranges of motion for pre- and post-feedback in both the lumbar and thoracolumbar movements. While this increase in activity indicates a change in the motor control strategy, it is possible that parameters of this specific task might not facilitate the redistribution of activity through biofeedback. The Ito test was specifically designed, and selected for use in this thesis, as it focuses the muscle contraction in the lumbar paraspinal region, and reduces compensation with alterative muscle contractions to maintain the task (Ito et al., 1996, Muller et al., 2010). As the design of the task is such that there is no mechanical ability to alter the task position, it might be possible that the biomechanics of the movement could not be sufficiently altered, similar to the effect described by Arvanitidis et al. (2019). This indicates that further investigations might focus on task which allow mechanical changes, such as the postural correction task, which might better facilitate changes in the distribution of activity. However, as non-normalised data were considered in this study, these values could be affected by other biological confounders, such as the electrode orientation relative to the fibre pennation angle or subcutaneous fat thickness (Kuiken et al., 2003, Hodges and Danneels,

2019). However, in this study there was not a suitable period of no movement, MVC or SMVC which could be used for the purpose of normalisation, a factor which should be considered for the continuation of this study.

While a previous study in this thesis (Chapter 3) has shown a difference in the distribution of activity between CON and LBP groups, this difference was identified over a progression to task failure, a condition absent here (Sanderson et al., 2019b). In the current study, this task was not completed to task failure as it was just one component of a series of tasks, therefore a time limit was used to minimise the chance of participants being unable to complete any further tasks. However, in the study by Arvanitidis et al. (2019), which assessed the effect of detailed biofeedback on muscle activity in the *trapezius* to task failure, the difference in centroid location appeared to be less pronounced during earlier stages of an endurance task. Similarly, other studies which have assessed muscle activation and endurance contractions, have also demonstrated increases in centroid movement in healthy participants as endurance time progressed (Falla et al., 2014, Farina et al., 2008). It is therefore possible that if this task was maintained for a longer period, CLNLBP participants might be better able to alter the position of the Y-barycentre using HDEMG biofeedback.

In the study by Arvanitidis et al. (2019), despite clear modification of muscle activity in response to the biofeedback, there was no functional benefit conveyed in the form of increased endurance time. Other studies which have used less detailed HDEMG biofeedback to elicit changes in muscle activity did not measure any outcomes relating to pain or exertion related to these muscular changes, making comparisons challenging (Gaffney et al., 2016, Samani et al., 2010). In the current study, there was no immediate improvement in PROMs (*e.g.* pain or exertion) following HDEMG biofeedback. It is possible that a programme of training is required over several sessions to build up functional changes. For example, a recent study

addressing the use of EMG biofeedback for tension headaches identified improvements in pain symptoms only after a training period of 15 sessions (Sobaniec et al., 2019).

The CNSLBP sample recruited for this study is comparable to the other samples from this thesis, reporting mild to moderate levels of pain, minimal to mild levels of disability (Breivik et al., 2008, Fairbank and Pynsent, 2000). The sample, as in other Chapters, consisted of active individuals as assessed by the IPAQ, indicating that despite pain levels the participants completed a typical range of physical activities (Craig et al., 2003). This proportion of high activity is unusual in a chronic pain population, but could be explained by the relatively young sample, experiencing mild pain and disability (Altuğ et al., 2016). In the PNRS outcome measure, only one comparison demonstrated a change following the use of biofeedback to alter muscle activity (Nicholas, 2007). Participants reported that following the biofeedback training, they believed that they were better able to follow physiotherapist advice to alter how they use their muscles. This preliminary finding indicates that the biofeedback maps may be useful in augmenting physiotherapist training programmes, but further research investigating self-efficacy using validated tools would be required to fully assess this.

6.4.1 – Reliability

As in all previous experimental Chapters, the unquantified level of reliability in the technique of HDEMG on the lumber region of individuals with CNSLBP limits the applications of these results. The exploratory nature of these results precludes any formal statistical analysis; therefore, the results would not have sufficient strength to form the basis of a clinical intervention at this stage. However, as the reliability is heretofore unquantified even if the results did indicate statistically significant changes, the confidence in the strength of the results would remain very low due to the unknown consistency in the technique (Guyatt et al., 2011c).

Therefore, in order to ensure confidence in the results presented in this study and develop the research further for potential clinical applications, research to assess the reliability of the technique is required in this population.

6.4.2 – Strengths and Limitations

This exploratory study is the first to assess the use of novel detailed, real-time wireless HDEMG biofeedback in a symptomatic population. The use of both static and simple dynamic tasks allowed participants to use the biofeedback in different contexts; and allowed for identification of the dynamic task as the task with greater potential for future investigations. Despite the preliminary nature of the investigation the methodology is rigorous, facilitating results which can influence further research in order to assess the feasibility of this technique as an intervention in people with CNSLBP.

As discussed in previous Chapters, the CNSLBP group presented with mild – moderate levels of pain. This sample is representative of a portion of people with CNSLBP however it does not fully investigate the range of CNSLBP presentations. As recruitment was not completed, the sample is underpowered and no statistical comparisons could be considered, limiting the application of the results. An unvalidated PSEQ tool was used in this study in order to directly measure the effects of the biofeedback, while this was effective, the use of a validated tool would offer more reliability in the results.

6.5 – Conclusions

The results of this exploratory study have demonstrated that the use of detailed HDEMG biofeedback can be used to instigate changes in the distribution of muscle activity in people with CNSLBP. In the postural correction task, an altered distribution of muscle activity was identified following biofeedback training, and persisted in the second session. Biofeedback during the Ito task facilitated a greater activation of the ES, but there was no change in the distribution of activity, potentially due to the constrains of the task. These preliminary results indicate that people with CNSLBP can use detailed HDEMG biofeedback to activate the caudal regions of the muscle, however there were no changes in the PROMs. Therefore, this technique requires further structured testing to assess the viability for use as an intervention. It is suggested that further research initially be conducted in the form of a feasibility study investigating the use of detailed HDEMG biofeedback in populations both with and without CNSLBP in order to refine the methods (*e.g.* task selection).

CHAPTER 7

GENERAL DISCUSSION

7.1 – Summary of Findings

Chapter one discussed the global mounting challenge of CNSLBP, and introduced anatomical and biomechanical factors which are believed to underlie symptoms in some cases. EMG and HDEMG were introduced here and previous research using both bipolar and HDEMG to investigate the influence of CNSLBP on muscle activity was discussed. Finally, elements of the body of research which have not fully been explored were identified as objectives for this thesis.

Chapter two reported a systematic review of the literature associated with the influence of CNSLBP on the magnitude of muscle activity during back-specific functional tasks (Sanderson et al., 2019c). This review indicated that while 23 individual studies had specifically investigated muscle activity there could only be weak recommendations regarding the influence of CNSLBP, due to the very low quality of evidence. A very low quality of evidence in this review indicated that there were no differences in the magnitude of muscle activity in CNSLBP. Evidence at the subgroup level also identified no differences; but there was greater variation in these groupings, specifically in the magnitude of muscle activity in the ES and during flexion and extension tasks. Additional research using more detailed novel HDEMG techniques was also recommended to identify more subtle differences in activity over a greater muscle area. This review gave a weak recommendation for no differences in the magnitude of muscle activity

between groups, however further high-quality research in the highlighted areas was identified as a key focus for future research.

In light of the results of this review, Chapter three reported an cross-sectional, observational study which used HDEMG to investigate the distribution of muscle activity in the lumbar ES during a static, prone trunk extension endurance task (Sanderson et al., 2019b). An Ito test was completed to task failure in samples with CNSLBP and pain-free control participants, and muscle activity and time to task failure were recorded. In this study, an altered distribution of muscle activity was identified in people with CNSLBP, favouring a more cranial and less diffuse distribution of muscle activity. People with CNSLBP also demonstrated a shorter time to task failure. These findings, measured on the most painful side in people with CNSLBP, indicated the presence of an altered motor control strategy during a static prone extension task in a painful lumbar region. However, it is unclear how this would affect muscle activity across the entire lumbar region or during a more complex task of daily life.

In order to answer these questions, Chapters four and five reported cross-sectional, observational studies which investigated dynamic lifting tasks of a varying level of complexity (Sanderson et al., 2019a). During these tasks, a more comprehensive approach to examining ES activity was taken, with four (13x5 channel) HDEMG grids covering the entire lumbar and thoracolumbar regions bilaterally. The results of both studies were similar to those found in Chapter three, indicated a more cranial, and less diffuse activation of the ES, characterised by systematically more cranially focussed contractions across all movements in both studies. During the multiplanar task, the groups of people with CNSLBP demonstrated less variability between sides in the centroid location; suggestive of a reduced ability of the muscle to adapt to the changing biomechanical demands of the task. In the multiplanar lifting task (Chapter five),

despite the complex nature of the task, consistently the CNSLBP group showed a greater normalised level of muscle activity.

Consistently within Chapters three to five a motor control strategy, characterised by a less diffuse and more cranially focussed contraction, was identified in participants with mild to moderate CNSLBP. In Chapter six, this aberrant pattern of activation identified was challenged; novel HDEMG biofeedback was used to explore if the caudal ES could be volitionally activated in people with CNSLBP. Participants were able to visualise their muscle activity in the form of a topographical colour map and use this information to alter their activation during postural corrections, demonstrated by a change in the distribution of the contraction caudally. While the distribution of activity was not altered for the Ito task, there was an increase in the magnitude of the ES activation throughout the contraction. These preliminary findings suggest that people with CNSLBP are able to use HDEMG biofeedback to alter the distribution of muscle activity in the ES, however further research is needed to assess the feasibility of the technique as an intervention.

7.2 – Distribution of ES Muscle Activity

The observational studies within this thesis identified a consistent altered spatial distribution of muscle activity within the lumbar ES. This pattern of activation was characterised by a more cranially focused centre of muscle activity and less homogenous contraction across the recorded area. This distribution of activity was identified during both static and dynamic tasks, and was also present during the pre-biofeedback condition within Chapter six. Interestingly, this result was identified equally when one grid was used and when four grids covered the lumbar and thoracolumbar regions (Chapters three-five). This

distribution supported the hypothesis that people with CNSLBP activated more cranial regions of the ES, such as the *longissimus thoracis pars thoracis* and the *iliocostalis thoracic pars thoracis* (Bogduk, 2005). However, it is important to consider that as reliability has not been established for this technique for the ES or in CNSLBP, there is a very low confidence in the cumulative quality of this evidence.

Previous studies have identified altered spatial distribution of activity in CNSLBP, most commonly characterised by an altered displacement of the centre of muscle activity in the cranio-caudal axis. In healthy individuals, the centre of muscle activity was shown to change with prolonged tasks, likely reflecting a redistribution of activity to avoid excessive localised fatigue (Farina et al., 2008, Tucker et al., 2009). However, pain appears to alter this relationship. In studies which have assessed the redistribution of muscle activity in the presence of experimental pain a clear shift in activity away from the site of pain induction, to a region which is not typically active, was demonstrated (Madeleine et al., 2006, Falla et al., 2017). In studies of people with CNSLBP, these individuals demonstrated less redistribution of activity than control participants during prolonged activations of the painful lumbar region (Falla et al., 2014, Abboud et al., 2014).

However, this result was not identified within studies reported in this thesis, instead LBP and CON groups demonstrated similar redistribution in muscle activity over time. Therefore, it is suspected that the systematically more cranial centroid identified could be the result of a pattern of muscle activation which specifically avoids the painful region. A very recent study has investigated the distribution of motor units in the *longissimus thoracis pars lumborum* and identified a non-uniform distribution of motor units, with distinct groupings in the cranial and caudal regions which do not span the entire lumbar region (Abboud et al., 2020). In their study, Abboud et al. (2020) identified task-specific preferential activation of motor units

in the cranial and caudal regions of the *longissimus* during axial rotation in healthy individuals. In the studies detailed in Chapters three to five, this pattern of activation was not identified in people with CNSLBP. Instead, a consistent pattern of activation was identified which is thought to be representative of a combination of the strategies employed in both CNSLBP and experimental pain participants described previously. It is therefore hypothesised that this pattern of activation is intended to utilise less painful regions and so facilitate the redistribution of activity throughout a task. This hypothesis would suggest that the cranial activation of the muscle is an example of pain-avoidance (Hodges and Tucker, 2011, van Dieen et al., 2017). In this paradigm, individuals experiencing pain would activate regions which are not typically active in order to reduce activity in painful regions, this activation is not thought to non-volitional. The activation of regions which are not directly pain-provoking, could indicate why there were similar redistributions of muscle activity, as this more cranial region may behave more like a pain-free muscle. However further research is required to investigate this.

The location and displacement of activity in the cranio-caudal axis are one element of the identified muscle activation strategy, but differences in the entropy across the grid also characterise this activation pattern. As a quantification of the homogeneity of signals across the grid, this measure identifies how diffuse the contraction is across the investigated area (Falla and Farina, 2008b). Where investigated within this thesis, there was systematically lower entropy across all results in LBP groups. These results were indicative of less diffuse contractions which show topographical heterogeneity in muscle activation. While this result does not specify the region in which these diffuse contractions are occurring, it does indicate a non-uniform distribution of activity (Falla and Farina, 2008b, Ferrari et al., 2018, Martinez-Valdes et al., 2019, Sanderson et al., 2019a). As the Y-barycentre is a measure of the weighted centre of the activation in the cranio-caudal y-axis, the combination of these factors describe

less diffuse and more cranially weighted contractions. While not assessed for statistical significance, the visual differences in topographical maps of muscle distribution appear to support this interpretation (sections 3.3.3, 4.3.2 and 5.3.2).

However, if a cranial and less diffuse activation is indeed interpreted as a preferential activation of less painful muscles; this would preclude the primary activation of the most biomechanically favourable muscle regions. As described in Chapter one, within the lumbar region the laminated morphology of the *longissimus* and *iliocostalis* there are short caudal fibres which connect directly to the caudal lumbar vertebrae (Bogduk, 2005, Macintosh and Bogduk, 1991). Following simple biomechanical principles, shorter muscle fascicles facilitate more powerful contractions, and longer fascicle lengths increase the range of motion around a joint (Palastanga et al., 2013). If the motor strategy here is indeed to avoid this painful region, then the contractions deselect these shorter muscle regions in favour of increased activation of only longer fibres which will be less able to sustain the weight of the trunk. As such this would lead to increased myoelectric fatigue as can often be identified in CNSLBP (da Silva et al., 2015, Falla et al., 2014), and ultimately influence pain symptoms. Thus, this form of pain-avoidance is likely to resolve into a 'vicious cycle' which could account for the greater level of pain rated by all participants following completion of the studies in Chapters three and five (O'Sullivan et al., 2018).

A less diffuse and more cranially focussed activation was identified in the studies within this thesis, however this finding appears to in contrast to the similar previously cited studies (Abboud et al., 2014, Falla et al., 2014). While these studies use similar samples and methods to those within this thesis, they are not identical and the biomechanical differences in the task positions may explain the differences. Abboud et al. (2014) described a similar lumbar endurance task, however in this instance participants were required to hold a position against

force, effectively creating an isometric task rather than a static position-matching task. As described previously, the difference between force-matching and position-matching tasks can cause significant differences in endurance time due to altered biomechanical demands (Russ et al., 2018, Thomas et al., 2011). Additionally, as described by Muller et al. (2010), the Sørenson test allows more compensation from muscles outside of the paraspinal region to complete the task, which might influence the contraction in the paraspinal region.

Falla et al. (2014) described a lifting task which elements of the methodology used here are based on, however the tasks explored here have been altered to change the focus of the task. In the study by Falla and colleagues, the task involved the repeated sagittal lifting of a box. Within this thesis, both the singular lifting of a box was tested, and repeated multiplanar lifting. In the monoplanar task, as participants did not have the opportunity to practice with a weighted box, the activation pattern could be more similar to a perturbation task than a repeated lift. In a task investigating perturbations in healthy and fatigued healthy participants, there were differences in muscle activity between groups (Jubany et al., 2017a), thus it can be expected that similar relationships could be seen in a singular lifting vs repeated lifting task which caused myoelectric fatigue. The multiplanar task involved a complex and changing biomechanical demand on muscles, which as can be seen from the results of the review (Chapter two) can, in some instances, be shown to present different myoelectrical demands on muscles (Du et al., 2018, Lariviere et al., 2002b). Furthermore, studies in healthy participants have also identified different demands and activation patterns in muscles during rotation movements (Kumar, 2010, Lee et al., 2005, Li et al., 2007). Thus, while these previous publications present similar tasks, differences in methodology could explain the differences in activity distribution.

The changing distribution of activity identified in Chapter five also presents an interesting pattern, whereby redistribution in control participants is not identified throughout a

task, instead redistribution is utilised to complete a task with varied biomechanical demands. The increased variation between sides in both the X- and Y-barycentre suggest that people with CNSLBP do not effectively recruit the lumbar paraspinal muscles to counter changing task demands. This difference was identified at the distal range of motion, a region in which the task demands will be highest and more differential activation required to effectively produce movement (Kumar, 2010, Lee et al., 2005). No previous study has examined the distribution of activity during a task this complex, and this result identifies a potential new area of investigation to understand this pattern in greater detail.

Finally, the distribution of muscle activity in the X (medio-lateral) axis has largely been found to not be affected by CNSLBP within the studies in this thesis, and more generally in the literature. In most instances, very few differences in activity in the X-barycentre have been identified in studies which have investigated this outcome in painful conditions in any muscle (Falla et al., 2017, Falla et al., 2014, Sanderson et al., 2019a, Sanderson et al., 2019b, Martinez-Valdes et al., 2019). One study previously identified displacement in the x-axis, but as this was investigating reliability in a healthy population and the magnitude of the shift was not statistically tested (Abboud et al., 2015). One potential reason for the relatively static X-barycentre compared to the Y-barycentre is the use of rectangular electrode grids, which cover a much larger cranio-caudal region of muscle than medio-laterally, reflecting the architecture and fibre direction of the muscles. However, in Chapter five a similar pattern of the distribution of activity at the distal range was found for both the X- and Y-barycentre, which significantly differed to CNSLBP participants. This study was unique among contemporaries for the complex task, and the comprehensive mapping of activity across the lumbar and thoracolumbar regions. It is therefore suggested that while shifts in the X-barycentre may be slight,

experimental methodologies should be expanded to include a variety of multiplanar movements and ensure that this variable is fully investigated.

7.3 – Magnitude of Muscle Activity

As comprehensively discussed within Chapter two, a very weak quality of evidence identified no differences in the magnitude of muscle activation in individuals with CNSLBP. Across 23 included studies, a majority of results indicated that there were no consistent differences in muscle activity regardless of task type or muscle studied. However, the cumulative quality of this evidence was very low, and trends were identified which suggested further high-quality research focussed on ES activation during flexion and extension tasks may identify some differences. Within this thesis, differences in the normalised muscle activity between groups were only identified in the multiplanar lifting task, detailed in Chapter 5. In this study, participants with CNSLBP demonstrated, on average, greater normalised muscle activity throughout the task. There were differences between groups for absolute RMS in the other studies reported here however, these have not been reported as the absolute RMS can be influenced by intrinsic biological factors (e.g. electrode orientation relative to the muscle fibre direction, subcutaneous fat thickness). This finding is broadly in line with the results of the systematic review and the following section considers how the results of these studies relate to the findings of the review, and what effect, if any, their inclusion would be likely to have on the overall conclusions.

The results presented in Chapter three were excluded from the review for the purposes of this thesis, as the investigation was methodologically based upon an earlier narrative iteration of the review. The Ito study presented in Chapter three would be categorised as a static prone

extension task, investigating activation in the ES (no difference in CNSLBP). The monoplanar lifting task (Chapter four) would be categorised as a dynamic lifting task, focussed on the ES (no difference in activation). The results of Chapter five would be considered as combined trunk tasks due to the multiplanar nature of the lifting task (greater activation).

As considered in each Chapter, each of these studies is considered to have low risks of biases (for reasons examined in detail in section 7.5.5 below). Due to the lower risk of biases, the inclusion of these studies would be expected to significantly strengthen the cumulative quality of evidence, increasing the GRADE rating for the ES subgroup from very low to low quality (Guyatt et al., 2011e). The similar levels of activation between groups identified in the prone extension task and the lifting task would further increase the evidence supporting no differences in muscle activity for tasks involving extension. The combined effect of all three studies would add evidence to support variable results for the ES due to task specific differences. Nonetheless, the addition of these studies would be unlikely to change the overall conclusion of no differences in the magnitude of muscle activity for the ES grouping, or for the ungrouped data (Fig. 7.1).

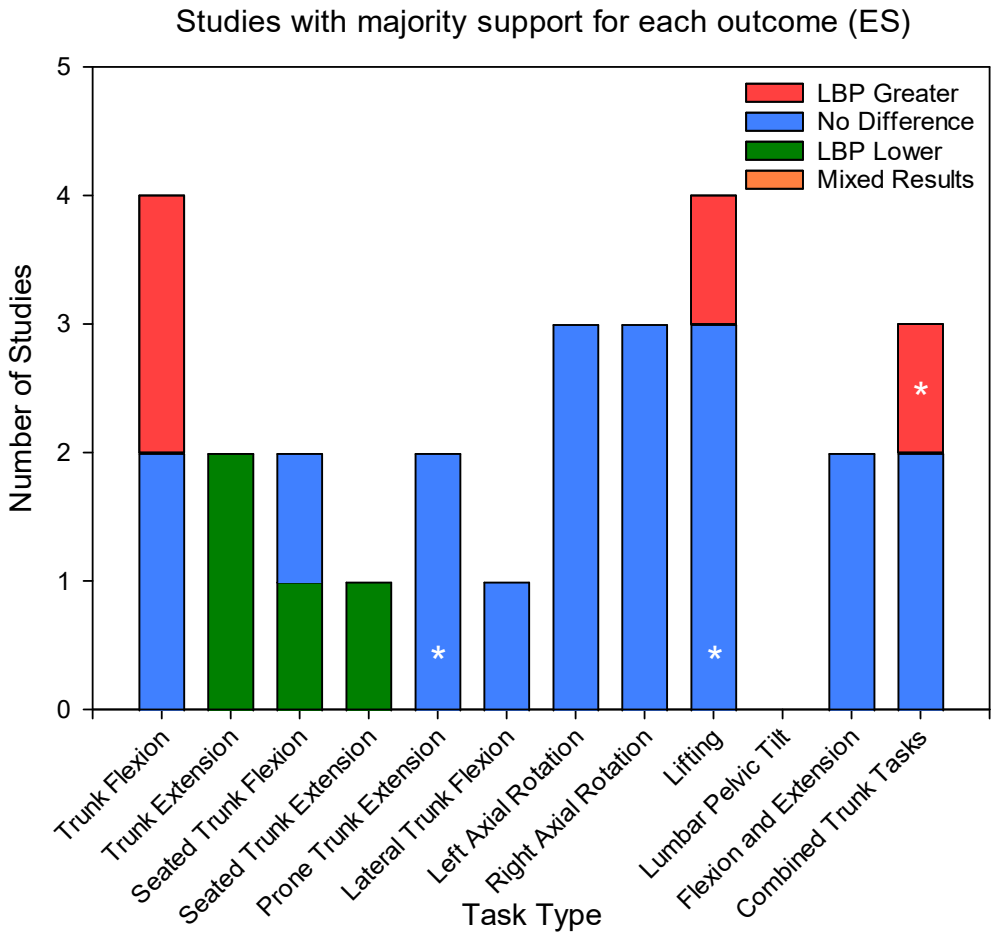


Fig. 7.1 – Modified version of Fig. 2.5, representing the number of studies supporting each review outcome, with the addition of studies from this thesis (marked by asterisks).

However, the addition of these studies to the review would have instigated the analysis of the regional distribution of muscle activation as an additional outcome of interest. In the original review, two studies which were included were known to consider the distribution of activity in the ES (Falla et al., 2014, Lariviere et al., 2002b). Falla and colleagues (2014) identified a reduction in the redistribution of activity, and Lariviere et al., (2002b) identified greater activation in the more cranial ES fibres. With the addition of the studies from this thesis, this would represent four studies which identified cranially focussed muscle activity. Due to

the low risk of bias among these studies, and the consistency of the results, it is speculated that this is likely to present a moderate quality of evidence to support a cranial distribution of muscle activity. However, as this was not a focus of the review in its current format, it is difficult to assert this, as distribution of activity was not extracted as a review outcome nor did the inclusion criteria facilitate the inclusion of all hypothetically relevant studies.

In the overall results of the review, there appeared to be greater variation in the activity identified for monoplanar flexion, and extension within the review, with three studies reporting a majority greater activation for CNSLBP in flexion and two showing a majority lower activation for extension. However, the overall result for flexion was no differences, and the result for extension was split between lower activity and no difference. EMG recording in these tasks was completed in static positions, and/or did not all involve the holding of an object. The review indicated that studies which investigated lifting included further examples of increases and no differences (Falla et al., 2014, Lariviere et al., 2002b, Lima et al., 2018). These tasks best represent the monoplanar lifting task described in Chapter four, and the experimental results presented in this thesis are broadly in line with those identified within the review with no differences identified in the normalised EMG data. However, as identified in the review, these data indicate that differences in muscle activation may be task-specific and different biomechanical demands play a role in the activation pattern demonstrated by CNSLBP participants. In a healthy population, Kumar (2010) identified an effect of different degrees of rotation on the activity of the trunk muscles, indicating that differing positions can place altered demands on the muscle activation. Similarly, in a different study, varied movement directions and ranges significantly altered the activity of the ES in a healthy population (Toren, 2001). In this instance, the task presented a hybrid between lifting and flexion, as only one repetition was completed, in contrast to the multiple repetitions for the lifting tasks, and to the unweighted

dynamic flexion and extension movements. Similar biomechanical differences were also identified in the multiplanar lifting task. This task was most comparable with the 'combined trunk tasks' category, which included a multidirectional lifting task with a lift from the floor and rotation to the right (Lariviere et al., 2002b). Again, due to the differences between this task and the multidirectional task, this biomechanical challenge is not comparable. As discussed in the previous section, the Ito test places specific focused biomechanical demands, with muscle activity focussed in the lumbar region (Muller et al., 2010). Neither of the studies included in the review which assessed prone trunk extension completed an established protocol, and arm position was varied. As such it is unclear what biomechanical demands were placed upon the lumbar regions, and how these could consequently affect lumbar paraspinal muscle activity (Cimbiz, 2006, Djordjevic et al., 2015). These studies demonstrate that slight changes in movement can place altered demands on tissues, which might influence symptoms and affect muscle activation.

7.4 – Potential Rehabilitation Applications

The research in this thesis suggests that a cranially focussed activation of the ES is common in people with CNSLBP. It is not possible to determine from the studies included within this thesis if this change is cause or an effect. However, within the vicious cycle theoretical framework, this relationship is less important as any change in muscle activation and movement could increase pain symptoms and so instigate further change (van Dieen et al., 2017). Thus, the biofeedback training explored within Chapter six was designed to break this cycle, by facilitating a change in muscle activation to closely resemble the pattern identified in pain-free individuals.

Across both the posture correction and Ito tasks investigated in this Chapter, preliminary results identified differences in muscle activity following biofeedback training. During the postural correction task, the use of the biofeedback enabled a more caudal distribution of muscle activity, and a greater magnitude of activity in the lower grid. During the Ito task, only the magnitude of activation was increased, with no change in the distribution of activity. In this experiment, as in another exploring detailed HDEMG biofeedback (Arvanitidis et al., 2019), while changes in the distribution of activity were identified, there were no short-term changes in PROMs following biofeedback training. However, typical intervention studies which involve training would take place over several sessions and the effects be built up over time (Izquierdo et al., 2016). For example, after 15 sessions of training, EMG biofeedback was demonstrated to have an influence on tension-type headaches (Sobaniec et al., 2019). General feedback training on a shorter scale can be effective, as demonstrated in a study assessing kinematic biofeedback during lifting, where a lower perceived exertion was identified after 20 minutes of training and correction (Boocock et al., 2019). However, a review of kinematic biofeedback training has only identified sporadic, small-moderate effects, so it is hoped that by altering muscle activity these effects might be more consistent, but this will require further investigation with additional arms to this design and longitudinal studies.

These differences appeared to make activation more uniform across the entire muscle in people with CNSLBP, a distribution of activity not previously identified in this thesis. This distribution of activation was more comparable to the CON group distribution of activation identified in previous studies, however due to methodological differences these results are not directly comparable. These exploratory results indicate that detailed HDEMG biofeedback appears to facilitate a change in the distribution of muscle activity in people with CNSLBP.

However, these results are preliminary, and further research is needed to assess the feasibility of this technique as an intervention to reduce symptoms in people with CNSLBP.

7.4.1 – Reliability

As has been considered throughout this thesis, the evidence presented appears to describe a novel aberrant distribution of muscle activation in individuals with CNSLBP with potential clinically applicability, however the question of reliability in the technique limits the confidence in the strength of the evidence (Guyatt et al., 2008). As considered in Section 1.4.4, reliability is a measure of the consistency of the data collection over repeated iterations, which accounts for systemic and random errors (Bruton et al., 2000). While previous studies have considered reliability in HDEMG in pain-free populations (Gallina et al., 2016, Martinez-Valdes et al., 2016, Martinez-Valdes et al., 2017), and estimated the correlations of the centroid location (Abboud et al., 2015), these results cannot be extrapolated to assert reliability for the technique in the lumbar region for individuals with CNSLBP. Therefore, while these results are preliminary in nature, they offer a promising line of investigation for further research but further work is required to strengthen the base of evidence. This work must ensure that the results are consistent with repetition and that error is quantified in order to determine the reliability of the technique within this sample. Only after this work is completed can the consistency element of the GRADE criteria be fulfilled and the results which are presented in this thesis be interpreted with greater confidence in the strength of the evidence (Goldet and Howick, 2013, Guyatt et al., 2011c, Guyatt et al., 2008). Until this reliability work is completed, it is difficult to estimate the true potential for this research in this clinical population as the level of reliability could alter the interpretation of the results.

7.5 – Evaluation of Methods

The methods used throughout this thesis have been guided by being a member of the CPR Spine research centre. This membership has influenced certain decisions and methodologies. In some instances, pragmatic decisions were made in terms of equipment and outcome measures in order to integrate this research into the portfolio of the centre, as will be discussed herein. However, this also presented the opportunity to use a range of novel techniques, and to draw on extensive expertise to support complex methodologies for detailed investigations.

7.5.1 – Experimental Tasks

Within the studies included in the review (Chapter two), there was little consistency in the methodology of the tasks explored, and even similar tasks are described in different ways. As previously discussed, it is suspected that some of the differences in muscle activity identified in this thesis could be associated with different task demands compared to other published studies. Within this thesis, the objective was to use back-specific tasks to investigate muscle activity in CNSLBP, and it is believed that the tasks chosen comprehensively achieve these objectives.

The Ito test methodology followed published guidelines to ensure a standardised approach was taken, and was reported in detail (Demoulin et al., 2007, Ito et al., 1996, Muller et al., 2010). Throughout the task both groups showed similar increases in exertion, and were able to sustain the task for over two minutes on average, indicating that the task was suitable for the purposes of testing lumbar endurance. This task was chosen over the Sørenson test which

is commonly used in published literature due to the reported greater specificity of myoelectric focus on the lumbar region described previously (section 3.2.3) (Muller et al., 2010). However, the Sørenson task was not assessed in this thesis so the comparison of results to previous studies is somewhat limited.

The lifting studies used similar methodologies to a previous study which investigated muscle activity in a population with CNSLBP (Falla et al., 2014). This ensured that the task was comparable within the field. The combination of standardised elements (*e.g.* the constant 5kg weight of the box and 2s metronome) and anthropomorphic personalisation (*e.g.* the shelf height) was intended as a means to simulate an occupational task and ensure the task was somewhat relevant to tasks of daily life. Some minor adaptations to the previous methodology were made regarding the anatomical feature used to define the height of the upper shelf and the time for each movement following consultation with members of the patient and public involvement panel, to ensure that participants with CNSLBP would be able to complete the task. Care was taken to ensure that these changes were minor and that the task was still broadly comparable to the earlier study (Falla et al., 2014).

7.5.2 – Power and Effect Sizes

The estimated sample sizes required to ensure a normalised distribution and statistical power were calculated *a-priori* and reported in each Chapter. In Chapter 3-5 these thresholds were deliberately exceeded in recruitment to ensure that the sample was larger than the minimum statistically estimated requirement, however in Chapter 5 technical faults and the resultant exclusion of data reduced the sample below the estimated threshold. In order to confirm that the *a-priori* calculations were sufficient, *post-hoc* power calculations were conducted to compute the achieved power using the reported effect sizes from each Chapter

using G*Power 3.1.9.7. In these calculations, power (1-β) was expected to be > 0.8 to indicate that the sample was sufficient.

The effect sizes in Chapter 3 (Ito test) were found to be large and ranged between 0.3 – 0.65, using these values, the power was found to be >0.8 for all calculations. The effect sizes in Chapter 4 (monoplanar lifting) were more moderate and ranged between η_P^2 = 0.05-0.13; following calculation the minimum effect also achieved power of >0.8. The moderate to large effect sizes and achieved power indicates that there is a low chance of type II errors in these studies (Button et al., 2013).

Chapter 5 (multiplanar lifting) did not reach the estimated required sample size due to technical issues, so it was expected and discussed in this Chapter that this is likely to affect the effect sizes and power accordingly. The effect sizes identified in this Chapter were very small and ranged between 0.0012-0.01, as such the *post-hoc* power calculation revealed that the power was low and <0.8 for all reported effects. This indicates that there is a substantial possibility that the results of this Chapter could be influenced by type II errors and greater sample sizes would be required to build confidence in the results (Button et al., 2013). However as considered in the discussion in Chapter 6, these results are indicative of group results which represent numerous individual effects which were not presented for the sake of brevity. For example, the gross difference in the location of the centroid across all movements was supported by 10 individual comparisons for each shelf movement, each of which indicated a significant difference between groups. Therefore, it is expected that the individual effects for each comparison were likely to be larger and subsequently have greater power to provide greater confidence in the results.

7.5.3– HDEMG Technique

7.5.2.1 - Electrodes

The electrode grids used in this thesis reflected the use of evolving HDEMG technology. The same style of electrodes were used for the first three experimental studies, as recording was completed on the same HDEMG amplifier (Quattrocento, OT Bioelettronica, Italy). These sensors had an electrode size of <5mm and an IED of 8mm, satisfying the criteria outlined to avoid the truncation of images outlined in Chapter one (section 1.4.5) (Afsharipour et al., 2019). This condition was also met in the final study, however in this instance the IED was 10mm, which is on the upper limit of acceptable (Afsharipour et al., 2019). This change in grid was made due to the use of state-of-the-art prototype wireless HDEMG amplifiers in Chapter six (Meacs, LiSiN, OT Bioelettronica, Italy) (Cerone et al., 2019). This system facilitated the real-time display of the activation maps in this study, and was perceived as potentially more clinically useful (due to the ease of use, relatively minimal equipment required and fast set-up). However, the Meacs system only allowed for 32 channels to be recorded through each amplifier, so a larger IED was used to ensure coverage over the lumbar and thoracolumbar region. The choice of electrode matrix was finalised for these experiments prior to the publication of recent guidelines, however the choice was confirmed as appropriate in light of the Consensus for Experimental Design in Electromyography (CEDE) project guidance (Besomi et al., 2019, Hodges, 2020).

7.5.2.2 - Electrode Placement

As discussed in Chapter one, the placement of electrodes has the potential to influence the results of surface EMG studies. Therefore, the basic placement of electrodes was consistent across all studies, with grids originating 2cm lateral to the L5 spinous process, but the region

covered differed between studies. Based on the anatomy outlined earlier, this region is known to cover the lumbar ES and furthermore, the distance from the midline avoids the inclusion of the *multifidus*, exceeding the minimum distance suggested in guidelines by Barbero et al. (2012). While no specific placement guidelines for HDEMG exist, the large size of the grid ensured that the location included the areas and regions suggested by bipolar guides for the lumbar ES (Criswell, 2010, Barbero et al., 2012, Beretta Piccoli et al., 2014).

While electrode placement was within these guidelines as far as possible, as the participants have varied anthropomorphic features it is worth considering the influence this may have. While the inferior border was aligned to L5, the superior border location could not be standardised as the grids have fixed dimensions. As such, it is possible that where individuals vary considerably in terms of height it is possible that different regions of the muscle may be being compared cranially. As such, it is possible that there may be differences in fibre direction underlying the grids, however, no studies have investigated this effect on HDEMG signals so it is not known to what extent this may have influenced results. As introduced in section 1.4.3, adiposity underlying the grid is known to directly influence signals, specifically affecting the impedance of signals under more substantial adipose tissue (Kuiken et al., 2003). This influence precludes the use of non-normalised signals for analysis as differences in the absolute amplitude could be linked to differences adiposity rather than myoelectric changes (Kuiken et al., 2003). Participants were matched for age and gender, and the recorded height and weight characteristics were comparable between groups in order to limit the effects of these anthropomorphic factors on the data; however, as grid locations were not guided by imaging the overall effect of these factors on the results is not quantified or known.

It is also relevant to consider how electrode placement could be affected and altered across the duration of the task. While the tasks described in Chapters 3, 4 and 6 were relatively

stationary and required small singular movements, the multiplanar lifting task examined in Chapter 6 was a complex and dynamic task. As such, precautions were taken to ensure that the grids were affixed firmly to the back using tape and adhesive pads, however it is likely to some movement may have occurred. If small shifts in the location of the grid occurred then this would be difficult to identify or indeed quantify the impact that it might have on the results of this study. However, as the same technique was used to attach, fix and secure the grids to the skin of participants in each group, it is unlikely that the grids moved more in one group compared to the other. In addition to the movement of the grids, it must also be noted that that even if the grid were to remain static with regard to the skin, it is not known during these movements how the relationship between the skin and subcutaneous muscle may vary which could also influence results. Nonetheless, while it is important to consider the potential confounders on results during dynamic tasks, it is also relevant to consider that these same confounders would produce changes during any dynamic task and the magnitude of these changes is not known.

7.5.2.3 – Additional Considerations

The main finding of this thesis relates to the altered distribution of muscle activity in the ES in individuals with CNSLBP. This outcome was primarily identified through the location of the centroid of the EMG amplitude map, which was calculated through the topographical plotting of RMS signals. In this thesis these data were reported in mm to two decimal places, however as reliability for this technique has not been established in this population or for this muscle it is not known if this is an accurate representation to the $1/100^{th}$ of a mm. The data were reported in this way for two reasons, the primary reason is that it was reflective of the group mean, which is unlikely to be an integer and secondarily this reporting is also reflective of centroid reporting in published literature (Abboud et al., 2020, Abboud et al., 2015, Falla et al., 2014).

Finally, it may be relevant to consider the potential impact of fatty infiltration and muscle atrophy in individuals with CNSLBP on the results of this study. It is well documented that individuals with CNSLBP may experience changes in the structure of the lumbar musculature, including alterations in the muscle fibre composition (Agten et al., 2020), the cross-sectional area of the muscle (Fortin and Macedo, 2013), and fatty infiltration in the muscle (Hodges and Danneels, 2019). However, it is not known how these changes influence muscle activity as measured by HDEMG, as no studies have correlated these measures. It is possible that the altered distribution of activity identified throughout this thesis is reflective of fatty infiltration in the caudal region of the ES, but as no imaging was used in the studies described in this thesis it is not possible to evaluate the impact of these potential changes on the results of these studies. 7.5.4 – Kinematics

The primary objective of the kinematic techniques in this thesis were to confirm that any differences in the muscle activity were linked to abnormal muscle activation rather than aberrant movement. For this purpose, the kinematic placement and analysis was thought to be effective, if not as comprehensive as possible.

For the Ito test in Chapter three, angular deviation of the trunk was monitored in real time with an electrogoniometer, but no further analysis was completed to assess kinematic changes. This is common practice in endurance tasks, and was sufficient to allow to the real-time monitoring of trunk position to determine task failure (Demoulin et al., 2006). However, afforded no possibility for post-test analysis of trunk position, or the relationships of other body regions. The two lifting tasks (Chapters four and five) used identical kinematic techniques, with data collected through an optoelectronic system. For these tasks, the analysis conducted was very minor compared huge range of possibilities for this technique (Cimolin and Galli, 2014). None the less, the analysis included here was appropriate for the aims of the studies. The

objectives of each were to assess muscle activity in the lumbar and thoracolumbar regions, and so the arrangement of markers overlying these regions was specifically chosen to allow regional analysis as described by Muller et al. (2016). Finally, in the biofeedback task, a system of IMUs were affixed to the skin to monitor movement throughout the tasks. In this instance, again motion was defined for the lumbar region and the thoracic region in the sagittal plane, but this analysis is not comprehensive of the possibilities (Seel et al., 2014, Ahmad et al., 2013).

Across the four experimental Chapters in this thesis, three distinct kinematic techniques and systems were used, based pragmatically on equipment availability within the research centre, to ensure that movement remained consistent between groups. Across kinematic techniques, it has previously been demonstrated that the comparability is low, and often differences can be identified between techniques during more complex tasks (Mundt et al., 2017). Previous studies have already assessed the kinematic differences between CNSLBP and control groups across a range of movements (Berglund et al., 2018, Cholewicki et al., 2019, Arjmand and Shirazi-Adl, 2005, Hemming et al., 2018, Sung, 2014), however this was not the outcome of interest in this thesis.

7.5.5 – Sample

Within this thesis the means of recruitment was consistently through poster and local advertising and was aimed towards individuals experiencing CNSLBP and pain-free controls. Furthermore, the recruitment technique and inclusion and exclusion criteria for control participants were reported thoroughly, as this was determined to be a source of bias in the review (Chapter two). The participants with CNSLBP within this study exhibited mild – moderate levels of pain, using the PNRS metric (Breivik et al., 2008), and exhibited minimal

to mild levels of disability (Fairbank and Pynsent, 2000). It is thought that these results, and others such as the PCS and the FABQ, indicated that the participants included in this thesis are broadly reflective of those experiencing CNSLBP but continuing to work, maintain high levels of physical activity (IPAQ) and complete tasks of daily life (Carlesso et al., 2018). As such, it is noted that there are people with CNSLBP who experience more severe levels of disability and pain. These individuals were not excluded from these projects, however it is speculated that they might be under NHS management and as such could not participate. A conscious decision was made to focus recruitment on individuals who were experiencing milder levels of pain which still permitted a normal range of daily activities (Carlesso et al., 2018). This focus was selected in order to complete initial studies in a population where the danger of provoking excessive pain or exacerbating symptoms was limited, and take the evidence to a wider CNSLBP population with varied levels of pain and disability in further studies. The studies reported in this thesis identify results in this population, and as no research has been conducted to assess the influence of varied pain levels on muscle activity, it is not known how or if these results might be affected by increased pain levels. Therefore, further research in this area should focus on the influence of greater levels of CNSLBP on muscle activity, or more generally if the level of pain has an effect on muscle activity.

7.5.6 – Questionnaires and PROMs

As discussed throughout this thesis, it was necessary at points to vary the PROMs used across studies. The primary motivator for these changes were pragmatic in nature in order to facilitate data collection under grouped ethical approval. Several tools remained consistent throughout the thesis (*e.g.* the PNRS and the ODI), ensuring that as a key outcome,

the measures for pain and disability were consistent throughout all studies. These specific tools were also identified among the most commonly used in research and clinical practice (Clohesy et al., 2018, Östhols et al., 2019). However, some tools were varied in this thesis (*e.g.* TSK and FABQ as measures of fear surrounding movement), in these instances the difference was pragmatic, whereby ethical approval was granted for several related studies, one of which required the use of the FABQ specifically. As outlined in sections 3.2.2 and 4.2.2, the use of either tool represents a valid and appropriate measure of this outcome and while neither tool are used commonly in clinical practice, both are accepted for use in clinical and research settings for CNSLBP (Clohesy et al., 2018, Östhols et al., 2019). Thus, as the outcome was still considered, and it was not a primary outcome for this study, the use of different but closely related tools was considered an appropriate minor limitation.

7.5.7 – Cumulative Quality of Evidence

A very low quality of cumulative evidence was drawn from the systematic review due in part to the inclusion of a large number of studies with high risk of bias, assessed by the modified NOS (Wells, Accessed 2018). As such, only weak recommendations could be drawn from the results of cross-sectional observational studies which have investigated muscle activity. In view of this, attempts were made to ensure that the studies within this thesis were reported clearly and that biases were limited. Similarly, as evaluated in section 2.1, flaws in CDs were identified in the methodology of previous systematic reviews of the literature. To assure higher quality within this thesis, the same AMSTAR-2 and modified NOS scales have been used to assess the risk of bias of studies in Chapters two, three, four and five. Chapter six was not assessed owing to the preliminary nature of the study.

The systematic review reported in Chapter two was assessed in the CDs and non-critical domains (non-CDs) according to the guidelines for AMSTAR-2, a tool designed to assess the quality in systematic reviews (Shea et al., 2017). This review was conducted according to a previously registered protocol (CD 1), and used a comprehensive search across many databases (CD 2). The individual reasons for the exclusion of each study was not reported, however grouped reasons for exclusion and the number of studies excluded during the full text stage have been reported (CD 3). Risk of bias was assessed and reported for each study (CD 4) and while no meta-analysis was performed, the justification for this and synthesis approach was reported (CD 5). Biases were considered and reported throughout the results and discussion and findings were reported with consideration to the limitations these imposed (CD 6), including publication biases (CD 7). Of the nine non-CDs two were not fully met by this review, non-CD 8 and 10. Data were not extracted in duplicate; however, data was assessed for accuracy by the second reviewer to identify and mitigate any errors (non-CD 8). Additionally, non-CD 10 was not met, which involved discussion of industry funding sources, however no studies were funded by industry, making this domain irrelevant for the purposes of this review. As such, it is evaluated that this review meets at minimum all CDs and all but one relevant non-CD's of this tool which indicates the overall quality is likely to be 'High' (Shea et al., 2017).

The study detailed in Chapter three was excluded from the systematic review (Chapter two) but as detailed in section 7.3, this study would be expected to be rated as high quality. If this study was not excluded, is likely to have improved the quality of evidence in the ES subgroup from very low to low. This assessment was driven by clear reporting in the domains specifically identified in the review as key examples of poor-quality studies. This included detailed reporting of inclusion and exclusion criteria for both groups, with both samples drawn from the same local population. Participants were age-and gender-matched during the

recruitment process. Both groups completed the same standardised task and had the same standardised electrode placement. Every effort was made to ensure that both the EMG and task descriptions were standardised, clear and detailed. Similar efforts were made in Chapter four and five, and recruitment was standardised to match the first study. All participants were again age- and gender-matched at the point of recruitment, and the EMG and task exposures were described in a thorough and detailed way. It is therefore believed that each study is likely to be assessed as high quality, with a low risk of bias. However, it is important to note that these ratings have been performed by the author of these studies, which is a source of bias in itself.

The cumulative strength of the evidence presented within these studies would be impacted as the reliability of the technique has not been quantified as discussed previously. In line with the GRADE criteria, if the strength of the evidence of the subgrouping was estimated the unknown reliability of the measurement technique (HMEMG of the ES in individuals with CNSLBP) would reduce the overall GRADE recommendation in the consistency category (Guyatt et al., 2011c).

7.6 –CNSLBP and Muscle Activation

The results presented here appear to fit broadly into the descriptions of the relationship between pain and alterations to movement and the muscle activation strategy. Hodges and Tucker (2011) outlined a theory to explain how people move differently when in pain. One of the principles in this theory described a redistribution of activity within or between muscles in painful conditions. The results of the observational studies within this thesis consistently identified an aberrant distribution of muscle activity in people with CNSLBP. No study within this thesis identified any differences in the redistribution of activity between groups (*e.g.* as

identified in Falla et al. (2014)). However, as discussed previously, the altered distribution of activity identified here could simply represent consistent redistribution of muscle activity to a different less painful muscle region. This pattern of activation is in line with the proposed theory, which states that redistribution could include the preferential activation of specific muscle fibres to reduce pain (Hodges and Tucker, 2011). However, in this theory the authors also describe changes in the mechanical outcome of the contraction. Where the kinematics related to contractions were assessed throughout this thesis, few consistent differences were identified, appearing to contradict this element. However, it is possible that differences were very subtle and/or related to changes in the mechanical outcome which were not assessed. The theory also describes a short-term benefit but a longer-term harm from the strategy (Hodges and Tucker, 2011). The results from the completion of the Ito test in Chapter three appear to provide evidence to support this element. In this study, while the movement could be completed with similar levels of exertion, the time to task failure was reduced overall. However, the same measure of exertion was used in the multiplanar lifting task in Chapter five, and the LBP group was found to have greater exertion at the end of the task, which would signify few short-term benefits.

As such, the biofeedback tasks described in Chapter six were designed to intervene in this pattern of adaptation and the potential for functional benefit to the participants was explored, such as reductions in pain or exertion. The preliminary results indicated that participants were able to alter their motor strategy and redistribute activity using the biofeedback. However, further research is needed to identify how these results compare to those of pain-free individuals and if these results could potentially cause benefits over a longer term.

7.7 – Overall Strengths and Limitations

The studies presented in this thesis have comprehensively investigated how lumbar muscle activity is altered in people with CNSLBP. The studies have used novel methodologies which have facilitated the identification of consistent differences in the muscle activation strategy. In order to confirm these findings across a wider area, and muscle activity was measured across both the lumbar and thoracolumbar regions, using consistent electrode placements. A comprehensive array of tasks was used including both static and simple and complex dynamic tasks throughout the studies in this thesis. As the contraction type was not shown to influence the differences in muscle activity in the review in Chapter two, this approach ensured that any differences related to contraction type could be identified. Furthermore, the dynamic tasks had different levels of complexity, intended to identify if effects were associated with the type of task. The work in this thesis also had a clear focus on individuals with mild/moderate CNSLBP, ensured by near identical inclusion/exclusion criteria for all studies and confirmed by comprehensive PROMs. This focus allowed for the identification of differences in muscle activity, without potentially causing injury, which can now be further investigated in individuals with more severe symptoms.

As discussed previously, a limitation in this thesis is that there is no reliability data to support the use of HDEMG on the ES in individuals with CNSLBP. As such, it cannot be assumed that the technique is reliable in this region on this population and as such, limits the interpretation and relevance of the results of the studies described herein. It is also important to consider the limitations imposed by performing studies which are reductionist when considered in the biopsychosocial framework (Adams, 2006, Turk and Monarch, 2018). As outlined in section 1.1.2, CNSLBP should be considered in the context of biological, psychological and

social factors, which are all believed to influence individuals' symptoms to a varied extent (Kamper et al., 2015). However, the studies in this thesis only consider a biological perspective within the biopsychosocial paradigm, and so these studies are limited as they do not consider fully all elements which might influence pain symptoms. Nonetheless, these studies add to the body of evidence from a biological perspective that there could be some changes in muscle activation in individuals with CNSLBP which may be relevant to address as part of a multimodal intervention. Further unified biopsychosocial studies are however required to develop this research to be clinically applicable. Furthermore, within this biological paradigm only the ES was investigated in this population. Previous research has indicated that individuals may experience changes in activation in any of the flexors and/or extensors muscles of the trunk (e.g. *multifidus, transversus abdominis*) (Hodges and Danneels, 2019, van Dieen et al., 2017, Yang, 2018). As outlined in section 1.2.1, the lumbar ES was selected in this thesis due to its functional role in trunk extension movements as described by Mawston and Boocock (2015) and the subcutaneous distribution of fibres (Hodges and Danneels, 2019). However, the consideration of only one muscle group may not represent the specific dysfunction in the individual and limits the applicability of the results of this thesis.

There are further limitations in this thesis as discussed in each Chapter. The LBP group experienced mild to moderate CNSLBP symptoms and minimal to mild disability, which may not be representative of the wider clinical population. As it is not understood how the distribution of muscle activity differs with different pain levels, it is not known if this is likely to limit the generalisability of this research and so presents an area for future investigations. While the characterisation of pain and disability was consistent, the other PROMs were pragmatically altered. While valid measures were still used throughout the thesis, this change limits the comparability between studies within this thesis. Similarly, as the IPAQ data was not

correctly collected in the study reported in Chapter three, this metric also cannot be compared between all studies.

7.8 – Key Learnings

7.8.1 – Retrospective analysis of Projects

As the process of developing a PhD thesis is in itself a learning experience, it follows that at the end of the process there are some elements of the thesis which may have been developed differently given the retrospective opportunity.

The primary consideration among this relates to the reliability in the technique of HDEMG. At early stages of development in this project it was thought that reliability from other body regions could be applied globally and this was evidenced by the ready usage of the technique in published literature. However, after discussion and consideration of the results in general, and in particular the small effect sizes reported in Chapter 5, specific reliability results could have enabled much stronger conclusions to be derived. The integration of a reliability study at the start of this thesis would have allowed for the development of the HDEMG technique throughout the thesis as a reliable measurement tool, and enhanced the confidence in the strength of the findings.

While reliability is a key consideration it is not the only element of the thesis which may have been approached from a different perspective upon reflection. The spatial distribution of muscle activity forms a cornerstone of the analysis in this thesis and is considered from three separate analyses; the centroid location, entropy across the grid, and subjective visual descriptions of the colourised maps. Initially, this subjective analysis was considered

appropriate, as the outcome was not intended to be a statistically quantified result; instead it was intended the be considered as additional evidence. However, as the focus of the thesis became closely linked spatial distribution of activation, more substantial quantitative analyses was considered, but it was not possible to retrospectively implement this within this work.

Finally, within Chapter 6, a novel approach to affixing the electrode grids was implemented after a discussion with the manufacturers of the adhesive foam. In this study, rather than applying custom cut foam to each grid and applying each at a spaced distance; a single continuous foam was used to ensure uniform spacing and limit movement of grids relative to each other. This technique appeared to be effective for this project, and would have been beneficial to implement for the projects described in Chapters 4 and 5 if demonstrated through reliability testing.

7.8.2 – Considerations for Future Work

Subsequently, the recommendations from this thesis to improve the methodology relate primarily to points considered in section 7.8.1. The first point of consideration is to recommend the development of reliability and validity data for this technique specifically for this body region and this clinical population. Reliability of surface EMG and in other body regions has previously been established; however, without the lens of reliability data it is difficult to draw firm conclusions or to assess how clinically useful this technique may be for individuals with CNSLBP. Additionally, it is recommended that in order to provide the most robust analysis of spatial distribution of activity quantitative techniques are used, for example similar to those described by Gallina et al. (2018). The final recommendation for future work relates to the fixing of grids, it is thought that using a single consistently spaced foam for grids fixed in tandem allowed for the more secure and accurate attachment of multiple grids.

7.9 – Future Research

The work contained in this thesis provides preliminary findings of a change in the distribution of ES activity in in individuals with mild-moderate CNSLBP. This pattern was characterised by a more cranial and less diffuse activation pattern in the ES across a range of functional tasks. However further work is required in order to establish reliability in the technique in order to increase the confidence in these findings. Subsequent research can then understand this pattern of muscle activity in the context of the level of pain and/or disability. Understanding this link is difficult due to the subjective nature of pain, but it is likely to require further observational studies with individuals with greater reported pain and/or disability; or studies which use experimental pain of varied intensities in control participants to emulate different pain levels.

A preliminary study was described in Chapter six which investigated the efficacy of displaying the pattern of activation to participants in order to facilitate the activation of the more caudal ES regions. While preliminary results appear positive in terms of a somewhat altered distribution of muscle activity, further work is required in order to fully assess the efficacy of this technique. The research described within this thesis is at a pre-clinical stage, however it potentially offers a new avenue for the development of an intervention in this population (Shahsavari et al., 2020). In order to achieve this, following reliability work, the next stage would be to complete a full feasibility study to assess the viability of the technique. Following this, a randomised controlled trial design is likely to be the next appropriate stage for this project, to assess the long-term benefits of the technique, both in terms of the muscle activation, and in pain and other PROMs.

8 – CONCLUSIONS

The initial systematic review identified a very low quality of evidence which suggested that there were no differences in the magnitude if muscle activity in people with CNSLBP across the paraspinal regions. The observational studies within this thesis then demonstrated that while there is not a consistent difference in the magnitude of ES activity in people with CNSLBP, there appear to be more consistent differences in the spatial distribution of muscle activation. People with CNSLBP were found to utilise a less diffuse and more cranially focussed contraction across the lumbar and thoracolumbar region during static, simple dynamic and complex dynamic tasks. However, across these studies there were few consistent differences in the spinal kinematics, indicating the use of a similar movement strategy despite an altered motor control strategy. This motor control pattern could be easily displayed to participants or patients and could present an opportunity for a novel exercise approach. The preliminary testing of this approach suggests that the distribution of ES activity can be altered, however the functional benefits are not immediately apparent. Further research in this field should investigate the reliability of this technique and then potential benefits of detailed HDEMG biofeedback in CNSLBP could be explored; first in a comprehensive feasibility study, and then in the form of a randomised controlled trial with extended follow-up periods.

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APPENDICES

Appendix 1 – Sanderson et al., 2019a

Appendix 2 – Sanderson et al., 2019b

Appendix 3 – Sanderson et al., 2019c

Appendix 4 – Prisma Checklist

Appendix 5 – Detailed Search Strategy

Appendix 6 – Modified Newcastle Ottawa Scale and Justification

Appendix 7 – Specific Outcomes from Each Comparison

Appendix 8 – Ethical Review, Consent Forms and Patient Information Sheets for Chapter Three

Appendix 9 – Ethical Review, Ethical Amendments, Consent Forms and Patient Information Sheets for Chapters Four and Five

Appendix 10 – Custom Low Back Pain Questionnaire

Appendix 11 – Ethical Review, Consent forms and Patient Information Sheets for Chapter Six

Appendix 12 – Modified Pain Self Efficacy Questionnaire

Appendix 13 – Copyright Permissions

Appendix 1 – Sanderson et al., 2019a

frontiers in Sports and Active Living

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People With Low Back Pain Display a Different Distribution of Erector Spinae Activity During a Singular Mono-Planar Lifting Task

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This study aimed to investigate the variation in muscle activity and movement in the lumbar and lumbothoracic region during a singular mono-planar lifting task, and how this is altered in individuals experiencing low back pain (LBP). Muscle activity from the lumbar and lumbothoracic erector spinae of 14 control and 11 LBP participants was recorded using four 13 × 5 high-density surface electromyography (HDEMG) grids. Root mean squared HDEMG signals were used to create spatial maps of the distribution of muscle activity. Three-dimensional kinematic data were recorded focusing on the relationship between lumbar and thoracic movements. In the task, participants lifted a 5 kg box from knee height to sternal height, and then returned the box to the starting position. The center of muscle activity for LBP participants was found to be systematically more cranial throughout the task compared to the control participants ($P < 0.05$). Participants with LBP also had lower signal entropy ($P < 0.05$) and lower absolute root mean squared values ($P < 0.05$). However, there were no differences between groups in kinematic variables, with no difference in contributions between lumbar and thoracic motion segments ($P > 0.05$). These results indicate that participants with LBP utilize an altered motor control strategy to complete a singular lifting task which is not reflected in their movement strategy. While no differences were identified between groups in the motion between lumbar and thoracic motion segments, participants with LBP utilized a less homogenous, less diffuse and more cranially focussed contraction of their erector spinae to complete the lifting movement. These results may have relevance for the persistence of LBP symptoms and the development of new treatments focussing on muscle retraining in LBP.

Keywords: high density EMG, muscle activity, EMG, low back pain, ergonomics

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INTRODUCTION

Globally, low back pain (LBP) is a leading cause of disability and has been since this metric was first reported in 1990 (James et al., 2018). Recent studies have suggested that there is a worldwide point prevalence of activity-limiting LBP of 560 million people (Hartvigsen et al., 2018). There is a large economic cost associated with the treatment of LBP and in the UK alone, the direct annual

healthcare costs of chronic LBP are estimated as £1.8–2.3 billion (Hong et al., 2013). In the USA, the wider economic impact of LBP is thought to be between $100–200 billion per annum (Duthey, 2013).

The prevalence and persistence of LBP is believed to be in part driven by exposure to manual handling, for instance lifting heavy weights in occupational tasks, or assisting moving patients in healthcare professions (Wai et al., 2010; Andersen et al., 2017; Silvetti et al., 2019). A meta-review of eight previous systematic reviews considering the effect of occupational tasks on LBP was conducted in 2011; identifying manual handling as a causal factor for LBP symptoms, whereas conflicting evidence existed for lifting (Kwon et al., 2011). Nonetheless, in more contemporary studies, occupational or routine lifting have been identified as a risk factor for the persistence of LBP symptoms (Andersen et al., 2017; Brandt et al., 2018). Most studies which investigate lifting in people with LBP have focused on repeated lifting movements, and while this is reflective of some occupational tasks, there are occupations which involve less frequent lifting which may still be relevant for the initiation and/or perpetuation of LBP. For example, several studies have investigated links between manual handling and LBP in nurses (Stobbe et al., 1988; Byrns et al., 2004), and while it is acknowledged that this is not a primary role of a nurse, the evidence supports a link between this occasional lifting and LBP.

Surface electromyography (EMG) can be used to evaluate the effects of both chronic and acute pain on muscle behavior (Madeleine et al., 2006; Lariviere et al., 2011; Falla et al., 2017) and classic bipolar EMG has been used extensively to quantify the effect of chronic or persistent LBP on muscle activity during lifting (Fabian et al., 2005; Ershad et al., 2009; Correia et al., 2016). In more recent studies, spurred on by advances in EMG technology, high-density EMG (HDEMG) has been used to evaluate changes in the spatial distribution of back muscle activity in people with LBP (Abboud et al., 2014; Falla et al., 2014; Martinez-Valdes et al., 2019; Sanderson et al., 2019). These studies have identified differences in the topographical distribution of erector spinae (ES) activity in people with LBP, including reduced re-distribution of activity during both dynamic and static tasks (Abboud et al., 2014; Falla et al., 2014).

HDEMG has also been applied to specifically evaluate lumbar muscle activity in people with and without LBP during lifting (Falla et al., 2014, 2017). In a study which investigated the spatial distribution of ES activity during a repetitive mono-planar lifting task (Falla et al., 2014), participants with LBP were seen to have reduced variation in the location of the centroid of the EMG amplitude map, indicating less re-distribution of muscle during this task. Although the study revealed an altered distribution of lumbar ES activity in those with LBP, the findings were limited to the specific region evaluated (i.e., lumbar ES unilaterally spanning a region from ∼L2 to L5). The findings were also potentially influenced by fatigue since the task was performed repetitively. In this study, participants with LBP were found to be less able to counter localized fatigue and redistribute activity to regions of the muscle which were not previously as active, instead repeatedly activating more cranial portions of the investigated region. It is possible that the cranial distribution and shift in activity identified in the LBP group could be due to the engagement of the thoracolumbar regions of the ES, which were not investigated. Similarly, this cranial focus of activity in participants with LBP was also identified in a static endurance task, with LBP participants focussing activation in only the more cranial regions of the assessed area (Sanderson et al., 2019). Several previous studies have investigated dissociation between lumbar and thoracolumbar contributions to movements in LBP populations (Langevin et al., 2011; Elgueta-Cancino et al., 2014), however the muscular contributions of these regions have not previously been measured.

Here we extend previous work by performing a comprehensive mapping of both lumbar and thoracolumbar muscle activity during a single repetition of a mono-planar lifting task in order to specifically examine the influence of LBP in the absence of a fatiguing task. Additionally, we record spinal kinematics in a segmental arrangement (Muller et al., 2016) to quantify differences between movement in the lumbar and the thoracolumbar regions of the spine.

Specifically, the aim of this study was to apply HDEMG bilaterally over the lumbar and thoracolumbar ES and utilize segmental spinal 3D kinematics to assess for potential differences in the spatial distribution of ES muscle activity and movement during a singular lifting task. We hypothesized that LBP participants would display a different distribution of ES activity during the lifting task characterized by a shift of activity away from the lumbar region toward the thoracolumbar region. Additionally, we hypothesized that this difference in muscle behavior would be reflected in a different movement strategy characterized by less lumbar spinal motion in those with LBP.

METHODS

This study was an observational cross-sectional study, conducted at the Centre of Precision Rehabilitation for Spinal Pain at the University of Birmingham between 2017 and 2018.

Participants

Participants aged 18–65 were recruited via poster and social media advertisements from the students, staff, and community of the University of Birmingham. Participants with LBP were considered for this study if they had experienced LBP symptoms for more than half of the days of the previous 6 months (Dionne et al., 2008), and were not under current healthcare management for their LBP (a requirement of the ethical committee). Participants for whom LBP symptoms were related to trauma, fractures, or spinal stenosis were excluded. Additionally, the presence of radiating pain down the leg was an exclusion criterion. Age- and gender-matched control participants were recruited who had no history of low back or lower limb pain. Participants from both groups were excluded if they were on high doses of anti-inflammatories (>30 mg morphine equivalent dose), were pregnant, or were experiencing any concurrent systemic, rheumatic or neuro-musculoskeletal disorders which could confound testing.

Questionnaires

Prior to commencing data collection, participants were asked to complete several questionnaires in order to assess their baseline characteristics. A bespoke back pain questionnaire was used to collect information relating to the characteristics, duration, and severity of participants LBP. Within this questionnaire, participants were asked to rate their current and recent levels of LBP on an 11-point numerical scale (Breivik et al., 2008). The general health of the sample was assessed using the SF-36 (V2), which has been shown to be a reliable measure of physical and mental health (Walsh et al., 2003). The International Physical Activity Questionnaire (IPAQ) was used to gain metrics on the level of physical activity within the participant cohorts in the week prior to data collection (Craig et al., 2003). The level of disability within the groups was assessed using the Oswestry Disability Index (ODI), a questionnaire which has previously been shown to be reliable in samples with lower levels of disability, as was anticipated (Fairbank and Pynsent, 2000). In order to assess any fear surrounding movement or relating to their level of pain, the participants were asked to complete the Fear Avoidance Beliefs Questionnaire (FABQ) and the Pain Catastrophizing Scale (Waddell et al., 1993; Osman et al., 1997). The Depression, Anxiety and Stress Scale (DASS-21) was also completed to identify the levels of mental health within the groups (Lovibond and Lovibond, 1995; Henry and Crawford, 2005).

Experimental Task

The experimental task consisted of lifting a 5 kg weighted box between two shelves situated anterior to the participant, simulating an occupational lifting task (Falla et al., 2014). To ensure the correct adjustment of shelf height and distance from the subject, several anatomical features were identified by palpation and measured on each participant. The lower shelf (S1) was set at the height of the lateral femoral epicondyle, the upper (S2) at the height of the sternomanubrial junction. Measured from the midpoint of the feet, the shelving was placed the distance from the acromion to the ulna head anterior to the participant (**Figure 1**).

To complete the task, subjects were required to stand in a quiet standing position, with their heels 17 cm apart and feet at a 14° angle to each other (McIlroy and Maki, 1997). During the task, participants lifted the 5 kg box (35.5 × 29 × 13.5 cm) between the shelves starting at the lower shelf. The speed of the task was controlled by a metronome with 2 s allocated to each movement between shelves followed by a rest of 2 s.

The task was standardized by using a universal weight of 5 kg for all participants, and providing identical instructions on how to complete the task, including instructions to prevent the movement of the feet and limit movement at the knee. These instructions were followed by a demonstration of the movement by a researcher, after which each participant was allowed to practice one timed movement with an unweighted box. Following familiarization with the task, the subjects completed a single cycle of lifting and lowering of the box.

This task was piloted extensively prior to the commencement of data collection to ensure that participants could complete the movement and LBP symptoms were monitored closely.

Experimental Set-Up

Electromyography

Surface HDEMG signals were recorded using four semi-disposable 13 × 5 2D electrode grids (OT Bioelettronica, Turin,

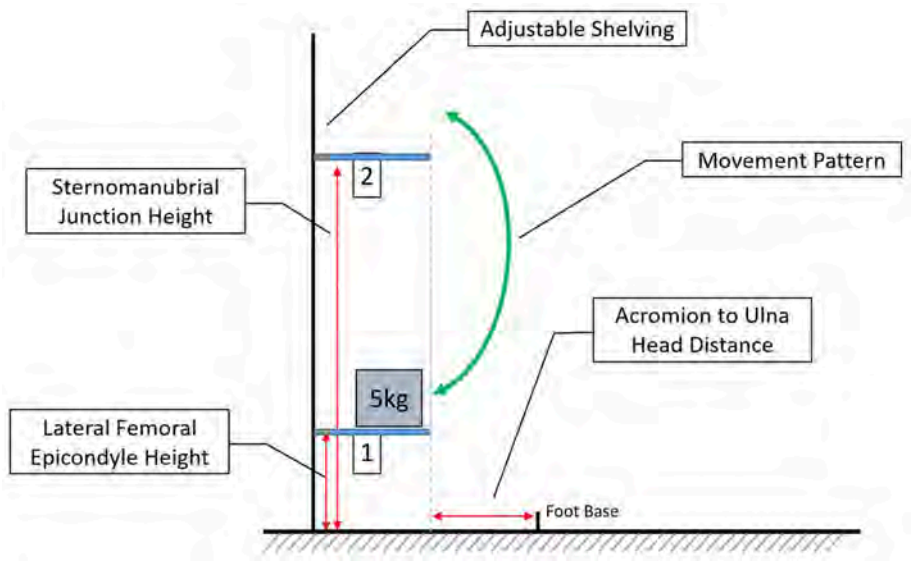


FIGURE 1 | Depicting the experimental set-up, with adjustable height shelving and the anthropomorphic characteristics which determine height and placement. Foot base describes the midpoint of the feet and the arrow indicates the movements between shelf 1 and shelf 2 (not to scale).

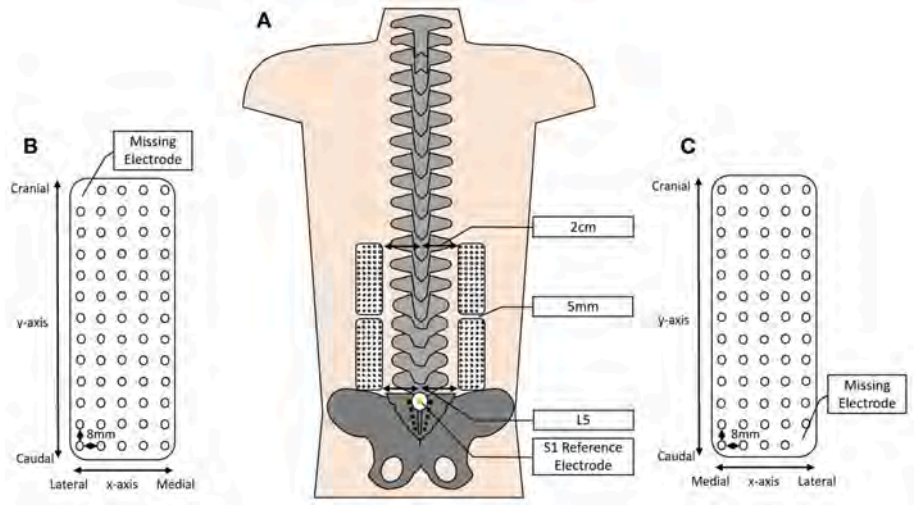


FIGURE 2 | Depicting **(A)** the approximate positioning of the HDEMG grids over the lumbar and lumbothoracic erector spinae (ES), 2 cm lateral to the spinous processes and spaced 5 mm between grids; **(B,C)** a schematic of the HDEMG electrode grid depicting the inter-electrode distance, the positioning of the x- and y-axes and showing the location of the missing electrode (not to scale).

Italy). Each electrode grid comprised of 64 electrodes spaced evenly with an 8 mm inter-electrode distance (**Figure 2**). The electrodes were adhered to the skin bilaterally, beginning at the level of the L5 spinous process and extending to approximately the level of T8–T10 depending on the height of the participant.

The electrode grids were prepared by first affixing a custom double-sided adhesive foam pad with holes for each electrode to the surface of the grid (SPES Medica, Genoa, Italy). The cavities created by the foam pad were filled with an electro-conductive paste. Before the electrodes were applied, the skin was prepared in order to reduce impedance and improve the quality of the bioelectrical signals recorded. First, the skin in the region that the electrodes would be placed was shaved and subsequently cleaned with an abrasive paste (SPES Medica, Genoa, Italy) and finally cleaned with water.

In line with previous studies, the lower grids were attached 5 cm lateral to the lumbar spinous processes, beginning at the level of L5 (Falla et al., 2014; Martinez-Valdes et al., 2019; Sanderson et al., 2019). The upper grids remained 5 cm lateral to the spinous processes; however, the inferior border was affixed to the skin 5 mm cranial to the superior border of the lower grid (**Figure 2**). Reference electrodes were placed on prepared skin overlying the S1 spinous process and the right medial malleolus.

EMG signals were sampled at 2,048 Hz and amplified by a factor of 150 (400 channel EMG Amplifier Quattrocento, OT Bioelettronica; −3 dB, bandwidth 10–500 Hz) before analog to digital conversion by a 16-bit converter. Recorded signals were saved on a computer hard drive and processed offline using custom MATLAB code (The Mathworks Inc., MA, USA). Each electrode grid recorded 64 monopolar signals, in this experiment two grids were used bilaterally equating to 128 monopolar signals per side. These signals were processed by filtering the signals using a 20–350 Hz 2nd order Butterworth bandpass filter (Gallina et al., 2011; Murillo et al., 2019), and the upper and lower grids combined at the intersection to create large left and right grids.

In order to best evaluate the distribution of muscle activity across this large region, monopolar signals were used for the following analysis. For each movement phase (S1-2 and S2-1), signals were divided into two equal epochs. The amplitude (RMS) was calculated for each signal and epoch, and these values were used to create topographical maps of the muscle activity. As described previously, the location of the centroid in the x- and y- axes was calculated from these topographical maps (Tucker et al., 2009; Falla et al., 2017; Sanderson et al., 2019). Additionally, values for the complexity (entropy) of the signals were calculated for each epoch, this measure indicates how homogenous the contraction was across the measured area, with a reduction in this value indicating a more heterogeneous contraction (Martinez-Valdes et al., 2019). The RMS and entropy were averaged across the large grids to obtain one value for each side.

Motion Analysis

Three-dimensional kinematic data were recorded using an 8-camera stereo-photogrammetric array (Smart DX, BTS Bioengineering, Milan, Italy). Retroreflective markers were adhered on the participant's skin overlying anatomical landmarks which were identified by palpation. The landmarks chosen for this task included unilateral points on the spinous processes of C7, T6, T12, and S1; and bilaterally over the remaining landmarks; 10 cm lateral to the spinous processes of T6 and T12; the iliac crest on the mid-axillary line; the lateral femoral epicondyle; the lateral malleolus, the head of the fifth metatarsal and the calcaneal tuberosity. The pattern of marker placement on the back allows the spine to be split into functional areas as described previously by Muller et al. (2016). Thus, the markers overlying the spine and lateral areas were used to create the Lumbar Segment (LS) and Thoracic Segment (TS) (**Figure 3**). Finally, to correctly identify movement events throughout the task, additional markers were placed on the outside edge of each shelf and on the edge of the box which was to be lifted.

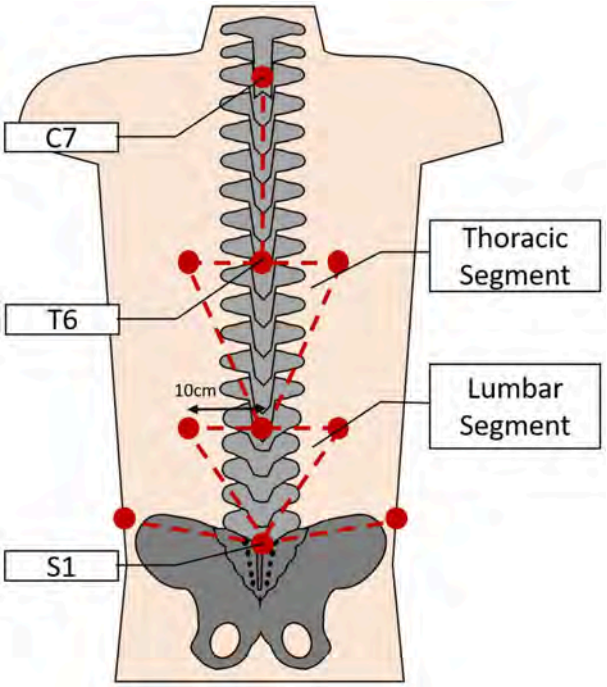


FIGURE 3 | Depicting the approximate locations of the retroreflective markers on the back (lower limb markers not shown) and the subsequent segmental model used for analysis of spinal movements during the task (not to scale).

Throughout the lifting task, 3D kinematic data were recorded continuously and sampled at 150 Hz. A trigger signal from the HDEMG amplifier was recorded alongside the kinematic data in order to allow synchronization between the devices. All data were saved on a computer hard drive for offline processing.

Analysis of the 3D data was completed using the BTS SMART software suite and custom analysis protocols (SMART Tracker, SMART Analyser; BTS Bioengineering, Italy). Raw 3D data were tracked and labeled using custom kinematic models and any errors in the tracking were corrected to remove artifacts. Then, individual 3D data points were interpolated and then filtered using a 5 Hz Butterworth low-pass filter to ensure that each track was suitable for further analysis. Finally, the movements to each shelf were identified, and the 3D tracks were cut in order to separate data into movement from S1-2 and S2-1. For the spinal segmental analysis, a reference axis was created for each segment (TS, LS), which was applied to a virtual point in the center of the segment. The Euler angle was calculated between these axes in order to understand how the segments moved in relation to each other throughout the task.

Statistical Analysis

Statistical analysis was completed using Statistica Version 13.3 (Tibco, USA), with an alpha level set at 0.5.

Sample Characteristics

Questionnaire responses were evaluated according to their respective guidelines (Waddell et al., 1993; Osman et al., 1997; Fairbank and Pynsent, 2000; Craig et al., 2003; Walsh et al., 2003; Henry and Crawford, 2005). Any differences between groups in demographic and questionnaire data were identified and tested for significance using student *t*-tests.

Motion Analysis

In this task, movement primarily occurred in the sagittal plane, thus for the motion analysis component of this study, the data considered involves only the movement around the horizontal axis in the sagittal plane. In order to understand differences in the movement strategy between groups, data were temporally normalized into 100 epochs representing 100% of the movement, and have been considered in terms of the shift from the first epoch. In order to achieve this, the angle between segments in the first epoch was considered as a zero-point, and was subtracted from each subsequent epoch, leaving just the deviation from epoch one. Any differences between groups for the movements were identified and tested for statistical significance using repeated measures ANOVA assessments with factors of group (LBP/CON) and time (100 epochs).

HDEMG

Analyses were conducted considering both absolute values (right and left) and, in line with several previous studies, comparing the most painful side for the LBP group to the right side of the control group (Falla et al., 2014; Sanderson et al., 2019). The choice of the right hand side for CON participants is reflective of previous investigations using this side, and of the mono-planar nature of the task.

Where no significant differences were identified between the first and second epochs of each movement, and thus to improve clarity in the results, the mean values across the pairs of epochs have been reported. Differences between groups were identified using factorial ANOVAs with factors of Group (LBP/Control), Side (Left/Right), Movement (S1-2/S2-1), and Epoch (Lifting/Lowering).

Topographical maps of the muscle activity were created from the absolute RMS values for each group. As the spatial distribution data were presented in the form of an image, only qualitative analysis was possible. The maps were classified by two independent raters in terms of the pattern of the distribution of activity. Each rater classified each map as either "diffuse activation," "predominantly diffuse," "cranial activation," or "caudal activation." Ratings were conducted independently and percentage agreement scores were calculated between raters (AS/EMV).

RESULTS

Sample Demographics

Fourteen control (CON) and eleven LBP participants completed the lifting task. There were no significant differences in the demographic characteristics between groups, with no differences identified in the mean age, BMI or gender distribution between groups (all $P > 0.05$). The LBP reported a mean current pain level of 2.59/10 and ODI score of 16.1.

The questionnaire data revealed no significant differences in the level of physical activity between groups (measured by the

IPAQ; $P > 0.05$) or the level of mental health (measured by the DASS-21 and mental component summary (MCS) portion of the SF-36; both $P > 0.05$). Significant differences were identified in measures related to back pain. The LBP group demonstrated higher levels of disability as measured by the ODI ($P < 0.0001$) and lower levels of physical health as measured by the physical component summary (PCS) portion of the SF-36 ($P < 0.0001$). Additionally, members of the LBP group showed higher levels of fear avoidance behaviors ($P < 0.0001$) and pain catastrophizing ($P = 0.001$) related to their LBP symptoms. Full demographic information from this sample is presented in **Table 1**.

Muscle Activity

In all analyses, there were significant systematic differences in the location of the centroid of muscle activity in the cranio-caudal direction (y-axis co-ordinate). Across both shelf movements, in both the analyses comparing the absolute data and the painful side analyses, the location of the y-coordinate of the centroid was systematically more cranial in the LBP group than in the control group. For the movement from S1-2, when comparing the absolute values, the average position for the y-coordinate of the centroid for the control group was 75.9 ± 8.4 mm cranial of the reference electrode, whereas for the LBP group, the centroid was 81.5 ± 7 mm cranial, a difference of 5.56 mm ($F = 12.13$, $P = 0.0008$). Similarly, for the movement from S2-1 the centroid was 76.1 ± 8.1 mm cranial for the control group whereas it was 82.6 ± 8.9 mm for the LBP group, a mean difference of 6.47 mm ($F = 14.25$, $P = 0.0003$; **Figure 4**). Similar results were identified in the comparison of the painful side and the right hand side for the control group. On average the y-coordinate of the centroid was 4.02 mm more cranial in the LBP group for the movement from S1-2 ($F = 4.08$, $P = 0.049$), and 5.56 mm more cranial for the movement from S2-1 ($F = 5.71$, $P = 0.021$).

The difference in the spatial distribution of activity was reflected in the topographical maps of muscle activity across the lumbar and thoracolumbar ES. From observation of the maps, the LBP group displayed a more cranial distribution of activity, while the control group showed a more even distribution across the entire muscle (see **Figure 5** for a representative example). When two individuals independently (R1/R2) classified the distribution of activity, for movement S1-2 the LBP group showed a more cranial distribution of activity in 7/11 (R1) or 9/11 (R2) cases whereas the CON group showed an even distribution across the region in 11/14 (R1) or 13/14 (R2) cases (84% reviewer agreement). Similarly, for the movement from S2-1 the LBP group demonstrated a more cranial distribution of activity in 6/11 (R1) or 8/11 (R2) cases and the CON group showed an even distribution in 12/14 (R1) or 11/14 (R2) cases (88% reviewer agreement).

When comparing the absolute values for entropy to evaluate the homogeneity of muscle activity, the control group had systematically higher levels of entropy for both movement phases, indicating a more uniform distribution of activation across the EMG amplitude map. For the movement from S1-2, the control group had an entropy of 6.93 ± 0.09 and the LBP group had an entropy of 6.89 ± 0.11 ($F = 4.7$, $P = 0.03$). For the movement from S2-1 the CON group entropy remained at 6.93 ± 0.09, however the LBP entropy was lower again at 6.86 ± 0.13 ($F = 8.3$, $P = 0.004$; **Figure 6**).

When comparing the mean results from each group, the LBP group also showed systematically lower RMS in both lifting directions. For S1-2, the average RMS for the control group was 48.14 mV greater at 196.33 ± 82.7 mV than the LBP group at 148.19 ± 57.1 mV ($F = 11.22$, $P = 0.001$). For the movement from S2-1 the mean control group RMS was 169.11 ± 75.6 mV and the LBP RMS was 140.27 ± 62.1 mV, a mean difference of 28.84 mV ($F = 5.08$, $P = 0.026$; **Figure 7**). In this task, both

TABLE 1 | Sample demographics for the control and low back pain (LBP) groups showing standard deviations.

Characteristic		Controls	LBP	*P*-Value
Sex		6 male, 8 female	5 male, 6 female	–
Mean age (Years)		27.36 ± 11.38	32.45 ± 16.27	–
BMI		23.13 ± 4.32	25.07 ± 2.58	–
ODI*		0.29 ± 1.07	16.1 ± 7.73	$P < 0.001$
PCS*		6.07 ± 7.50	19 ± 10.13	$P = 0.001$
IPAQ		72% (High)	82% (High)	–
DASS-21		9.29 ± 9.69	21.82 ± 29.59	–
FABQ*		3.38 ± 6.31	27.28 ± 11.31	$P < 0.001$
SF-36	PCS*	57.84 ± 3.95	47.75 ± 4.92	$P < 0.001$
	MCS	52.98 ± 3.16	46.33 ± 15.42	–
PNRS	Current pain	–	2.59 ± 1.64	–
	Average pain	–	3.36 ± 2.06	–

Where significant differences exist between groups the name of the outcome has been marked with an asterisk and a P-Value is displayed. PCS, physical component summary; MCS, mental component summary.

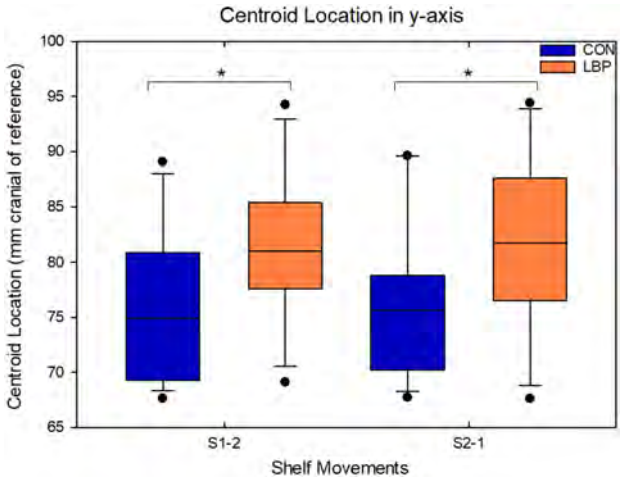


FIGURE 4 | Demonstrating the location of the y–coordinate of the centroid in the craniocaudal axis for movements from both S1-2 and S2-1 within the absolute data; significant differences between groups are indicated with an asterisk.

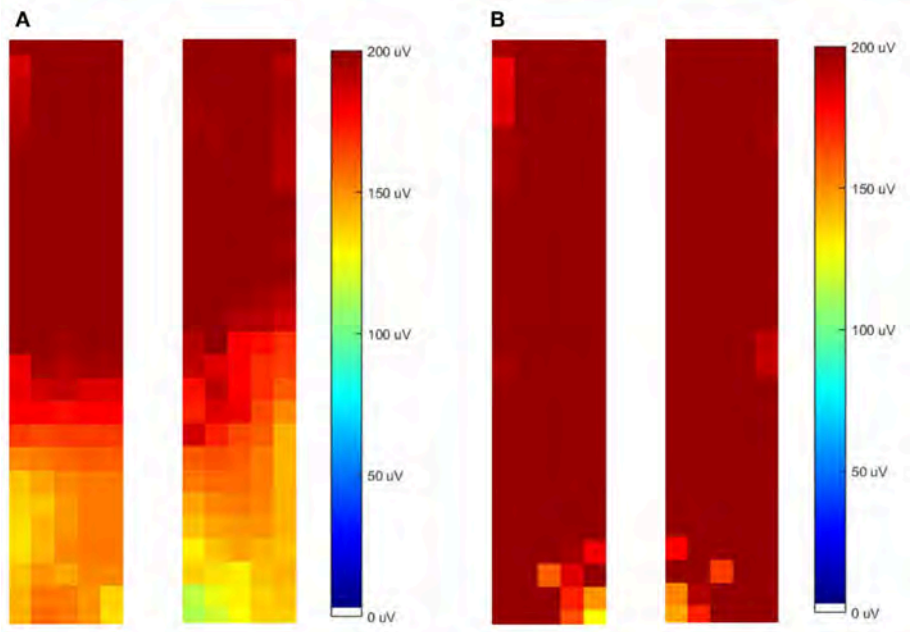


FIGURE 5 | Representative examples of the topographical distribution of activity in the left and right grids for both low back pain (LBP) **(A)** and control (CON) **(B)** participants.

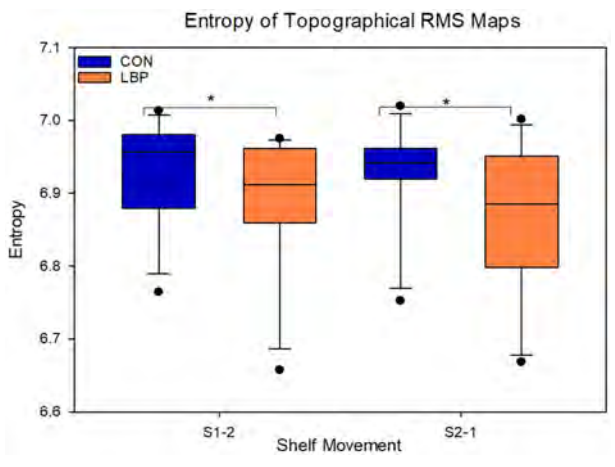


FIGURE 6 | Depicting the entropy of the low back pain (LBP) and control (CON) groups. Significant differences are marked with an asterisk.

groups also showed a significant difference in the RMS between the lifting and lowering epoch for both movements (S1-2—$F = 5.9$, $P = 0.02$; S2-1—$F = 26.0$, $P < 0.0001$) however no group interactions were present.

No significant differences were identified between groups for the location of the centroid in the mediolateral x-axis in any condition. When comparing the most painful side of the LBP group to the right side of the control group, there were no differences in mean x-coordinate of the centroid throughout the task ($P = 0.41$); and no difference in the shift of the centroid in the x-axis throughout the lifting task ($P = 0.43$).

Kinematics

There was no difference in the movement pattern used to complete the task. Participants in both groups used the same lumbar-thoracic segment movement pattern to complete both movements. No statistically significant differences were identified for the movement from S1-2 ($P = 0.81$) or from S2-1 ($P = 0.24$; **Figure 8**).

DISCUSSION

This study uniquely demonstrates that individuals with LBP utilize a more cranial and less diffuse distribution of ES activity during a singular mono-planar lifting task when compared to healthy controls, even while no difference in the kinematics of the thoraco-lumbar segments was observed. This study is the first to assess both lumbar and thoracolumbar ES contributions to a lifting task in both the painful and non-painful side in participants with LBP.

The participants recruited for this study were anthropomorphically comparable, with no significant differences in measures of BMI, age or biological sex between groups. Within the questionnaire results, there were also no differences between groups for the level of physical activity or for general mental health. However, understandably there were significant differences in measures designed to assess the impact of pain on day-to-day life. The LBP group reported higher levels of disability, pain catastrophizing and fear avoidance behaviors than the control group, consistent with previous research (Waddell et al., 1993; Fairbank and Pynsent, 2000; McWilliams et al., 2015). However, with the mean ODI score of 16/50 and average pain at the time of data collection of 2.6/10, it is

suspected that this group has only mild to moderate levels of pain and were highly functional (Breivik et al., 2008).

Evidence from previous studies has shown that LBP participants demonstrated reduced range of motion in spinal flexion when compared to healthy controls (Falla et al., 2014; Shojaei et al., 2017). This is likely due to the controlled nature of the task, as the participants received a demonstration of the movement and then were allowed to practice with an unweighted box to ensure that they completed the task correctly. Furthermore, they were asked to complete the task to the beat of a metronome to facilitate standardization. While other studies have similar pre-task training, as this task was short, it is possible that participants did not have the time to alter their movement strategy as pain was provoked or myoelectric fatigue developed as may be the case in longer tasks, however the myoelectric manifestations of fatigue were not formally measured here. Therefore, if the task were to be sustained for several minutes then it is possible that differences may become apparent. Furthermore, while this task design has not been investigated in a LBP population, an investigation in a healthy cohort reported low variability in movement, indicating that a movement with few repetitions might be expected to have little variability between subjects (Peach et al., 1998).

Consistently within the results of this study, there was less diffuse and more cranially focused ES activity in the LBP group. The differences seen from the topographical EMG amplitude maps were supported by the statistically significant differences in the location of the y-coordinate of the centroid and entropy between groups. Specifically, those with LBP performed the lifting task with greater activity in cranial regions of the thoracolumbar ES relative to the lumbar ES, resulting in greater heterogeneity of activity across the entire region examined. These findings suggest that the LBP participants engaged lower thoracic portions of the ES, that is the *iliocostalis lumborum pars thoracis* or the *longissimus thoracis pars thoracis*, to complete a targeted lumbar lifting task, relative to asymptomatic people.

The cranial shift of activity seen in the LBP group relative to the control group, likely implies the utilization of less biomechanically favorable muscle fibers to complete the lifting task (Bogduk, 2005). The structure of the ES in the lumbar region is laminated. The deepest and most medial fibers of the ES connect L5 to the PSIS, with fibers to each subsequent lumbar vertebrae forming progressively more superficially and laterally (Bogduk, 1980, 2005; Christophy et al., 2012). Thus, activation focused in the more cranial portions of the muscle is representative of primarily using the fibers extending to the higher lumbar vertebrae rather than the whole muscle. In this task due to the weighted box, which was held anterior to the participant, the forces through the lumbar spine were multiplied when the participant leant forward to complete the task (Han et al., 1995). Previous studies which have investigated the effect of dynamic lifting on this region have reported increases in both the

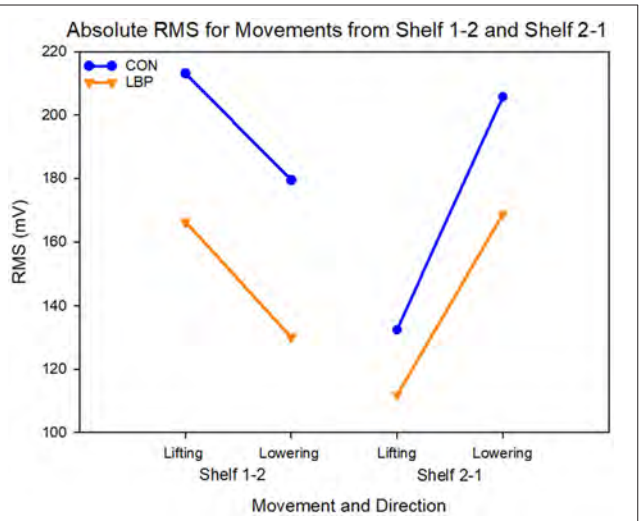


FIGURE 7 | Graph showing the absolute values for RMS in mV for each shelf movement across both lifting and lowering epochs.

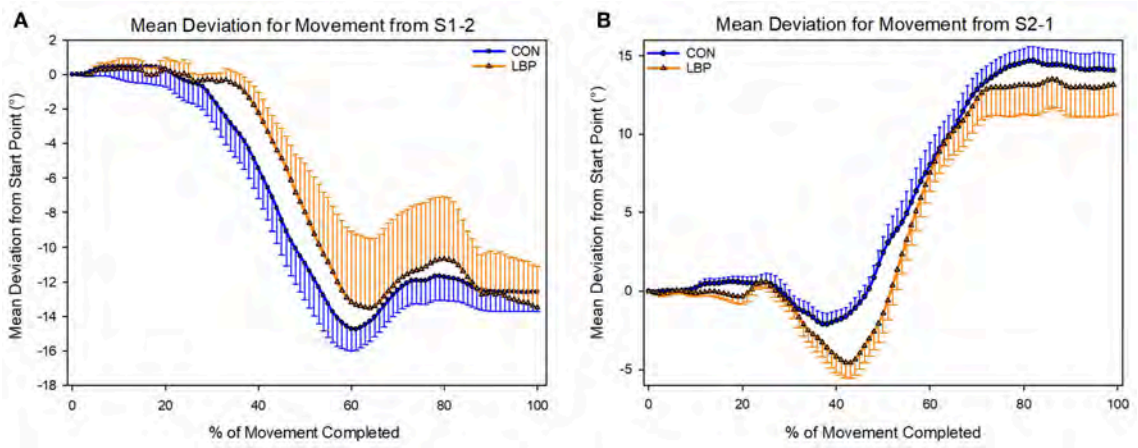


FIGURE 8 | Depicting the mean deviations from the start position used by each group to complete each shelf movement (**A**—Shelf movement 1–2; **B**—Shelf movement 2–1).

L5/S1 sheer forces and activity in the lumbar extensors (Arjmand and Shirazi-Adl, 2005). However, here we saw that activity was focused more cranially in LBP participants, potentially reducing the muscle fibers which were utilized to resist the increased sheer forces at the lower lumbar vertebrae.

The topographical redistribution of EMG activity within a muscle, during a fatiguing task, has also been observed in the trapezius muscle (Barbero et al., 2016). This phenomenon appeared to be correlated with the duration of the task and appears to be important to maintain the motor output (Farina et al., 2008). Notably, previous investigations including both dynamic and static tasks in presence of neck pain, consistently showed a redistribution of upper trapezius activity in a caudal direction (Falla et al., 2010, 2017). When considering the findings reported here, the variation in muscle activation occurs in a different manner but can be considered the output of the same adaptation strategy aimed to avoid pain or overload. Although, we cannot exclude that regional nociception can inhibit the muscle activity in some specific anatomical regions. In both cases the underlying physiological adaptations can play an important role in the clinical course of musculoskeletal pain.

STRENGTHS AND LIMITATIONS

This study is the first to assess muscle activity comprehensively over the lumbar and thoracolumbar region of the ES bilaterally during a lifting task. This allowed for the measurement of the effect that occupational lifting can have on individuals who already experience LBP; granting a deeper insight into the distribution of activity across the entire muscle region, and allowing the identification of a differing activation pattern.

A relatively small sample was used for this study which might account for some of the variability within the data. Nevertheless, the sample size was sufficient to reveal significant differences between groups. Additionally, the symptomatic participants were highly functional and reported only mild levels of LBP and so it is unlikely that these results can be extrapolated to those with more severe pain or acute LBP. Therefore, it might be difficult to generalize these results to patients with more severe symptoms, however it is speculated that even greater differences might be identified in patient groups with more severe symptoms or longer pain duration (Mannion et al., 2000; Arendt-Nielsen and Graven-Nielsen, 2008).

Here we designed a task to assess the effect of lifting a light load by an individual who has LBP; however, most occupational lifting tasks would comprise of repeated lifting, as in a factory setting, or multidirectional lifting. Nevertheless, our focus was to comprehensively evaluate muscle behavior and spinal movement during a single lift, without the presence of myoelectric manifestations of fatigue or provoked pain which could confound interpretation of the results, although as fatigue was not measured here this is slightly speculative. One final potential limitation of this study is in the qualitative interpretation of the spatial distribution data. As both reviewers are investigators in the study, there is a potential source of bias based on prior expectations, however reviewers were blinded to the group of the participant, and reviewed independently with good levels of agreement.

CONCLUSION

Participants with mild to moderate LBP utilize a different motor strategy to complete a lifting task which was characterized by a less diffuse, less homogenous, and more cranial focussed activation of the ES. This difference in muscle behavior was observed despite a consistent movement strategy between groups. This modified activation pattern identified within the LBP group could provide a basis for future treatments focussed upon retraining the lumbar musculature to ease LBP symptoms.

DATA AVAILABILITY STATEMENT

The datasets generated for this study will not be made publicly available as it includes confidential data.

ETHICS STATEMENT

Ethical approval for this study was granted by the University of Birmingham Ethics Committee (ERN_16-1389B), the procedures followed the Declaration of Helsinki and are reported in line with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines (Von Elm et al., 2008).

AUTHOR CONTRIBUTIONS

AS, EM-V, and DF contributed to the design of the study. AS and PK acquired the data. AS, CC, EM-V, DF, and MB performed the data analysis. Drafting of the manuscript was performed by AS and DF. All authors contributed to interpretation of the data, participated in revising the manuscript, and approving the final submission.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix 2 – Sanderson et al., 2019b

BMJ Open

The effect of chronic, non-specific low back pain on superficial lumbar muscle activity: a protocol for a systematic review and meta-analysis

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ABSTRACT

Introduction Chronic, non-specific low back pain is a major global cause of disability. One factor which might potentially contribute to ongoing pain is maladaptive variation in the level of activity in the lumbar musculature. Several studies have investigated this activity using surface electromyography, in varied muscles and during a number of functional activities. Due to differences in the applied methodology, the results have been difficult to compare, and previous reviews have been limited in scope. In this protocol, we aim to perform a comprehensive review of the effect of chronic low back pain on lumbar muscle activity.

Methods and analysis This protocol was informed by the Preferred Reporting Items for Systematic Review and Meta-analysis Protocols (PRISMA-P) and results will be reported in line with the PRISMA. Searches will be conducted on the Web of Science, PubMed, MEDLINE, EMBASE, ZETOC and CINAHL databases, along with a comprehensive review of grey literature and key journals. One reviewer will conduct the searches, but two independent reviewers will screen potential studies and assess the risk of bias within studies which meet the inclusion criteria. The Newcastle-Ottawa risk of bias tool, and the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) guidelines will be used to assess the quality of the data. Meta-analysis will be conducted where appropriate on groups of studies with homogenous methodology. Where studies are too heterogeneous to allow for meta-analysis, meta-synthesis will instead be completed, comparing results in terms of net increases or decreases of activity.

Ethics and dissemination This review aims to identify common adaptations of muscle activity in people with low back pain and it is expected that the results will influence future research directions and future rehabilitation approaches. The results will be submitted for publication in a peer-reviewed journal and presented at conferences.

Prospero registration number CRD42019125156

Strengths and limitations of this study

- First wide systematic search considering the effect of chronic, non-specific low back pain on muscle activity.
- This methodology allows for a wide range of tasks to be considered and included in meta-analysis.
- This protocol allowed for peer-review of the review methodology and so increases transparency and reduces bias.
- This protocol only accounts for observational studies, excluding randomised controlled trials, so the expected evidence level will be lower.
- While it would be beneficial to also consider the results of intramuscular electromyography, as the outcomes are too different, these results will be omitted.

INTRODUCTION

Rationale

Chronic low back pain (LBP) is a leading cause of disability, placing a high burden on healthcare services globally.[1 2] Recent point prevalence estimates suggest that at any one time, approximately 540 million people are experiencing 'activity-limiting' LBP.[3] Previous evidence suggests that of all those who experience LBP, 30%–40% will continue to experience symptoms beyond 3 months and thus become chronic.[4 5] Furthermore, as many as 85% of those who experience any form of LBP will have no diagnosable underlying pathology and are thus categorised as experiencing 'non-specific' LBP.[6] Therefore, efforts in healthcare research have included a focus on understanding the mechanisms underlying the maintenance of pain in chronic non-specific LBP (CNSLBP).

One potential physical contributing factor to LBP is variation in the level of activity of the lumbar paraspinal extensor muscles. This has the potential to change the load distribution on spinal structures, and thus contribute to the maintenance and/or perpetuation of pain.[7] However, despite several investigations, the exact link between the level of muscle activity and CNSLBP

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remains unclear.[7–10] The lumbar region is highly muscular, comprising subcutaneous contributions from the lumbar erector spinae (*iliocostalis*, *longissimus* and *spinalis*) and the superficial *multifidus*.[11] These muscles are considered particularly important due to their role in nearly all functional spinal movements and postural control tasks.[12 13] The most common technique used to investigate lumbar muscle activity is electromyography (EMG).[14–16]

EMG enables an understanding of muscles by recording the electrical activity during muscle contractions.[17] This activity can be measured using skin mounted electrodes, termed surface EMG (sEMG), or via needle electrodes known as intramuscular EMG. Surface EMG offers a non-invasive means to record the level of activity from the superficial musculature, either between two points on a muscle (bipolar sEMG) or across a 2D region of the muscle (high-density sEMG; HDEMG).[17] As sEMG is less invasive, it is more clinically useful and so studies which have investigated the effect of low back pain on muscle activity have often used sEMG electrodes over intramuscular techniques.[18] However, direct comparison between results remains challenging as these studies have incorporated varied methodologies and consequently often reported varied results including both increases and decreases in muscle activity as a result of LBP. These studies have used bipolar and HDEMG electrodes to measure activity within differing lumbar musculature as participants completed a variety of tasks including fatiguing, walking and endurance contractions.[14 15 19–22]

Previous reviews have attempted to synthesise these results to draw conclusions; however, these reviews have been focused on the investigation of activity within just one muscle, or during one task, for example, standing on unstable surfaces, or synthesising results drawn from one database.[8 10 23 24] While these reviews do answer specific questions, there remains a gap in the literature to assess what the overall effect of CNSLBP is on lumbar paraspinal muscle activity. In the most recent review of multiple tasks on muscle activity, with studies drawn from just one database, it was noted that differences were apparent in muscle activation between sitting and standing tasks in individuals with LBP.[8] Despite this finding, no previous review has utilised a systematic search strategy to compile these results across tasks and understand the gross effect of CNSLBP on lumbar muscle activity.

Thus, there remains no comprehensive systematic review to date which assesses the effect of CNSLBP on the level of muscle activity across all superficial lumbar musculature during a variety of functional tasks. Understanding the differences in muscle activity between individuals with CNSLBP and pain-free controls is relevant since understanding the most common adaptation of lumbar muscle activity to pain may lead to the development of new rehabilitation approaches for use in clinical practice.[18]

Objectives

1. To explore what differences are present in the activity of the superficial lumbar paraspinal musculature during functional tasks in individuals with CNSLBP, as measured by surface EMG.

If possible, dependant on the results of the primary objective and specifically if the data are suitably homogenous to allow meta-analysis, a secondary objective will be investigated.

2. To quantify the magnitude of changes in muscle activity associated with CNSLBP with regard to the type of functional task completed and the intensity/duration of LBP symptoms.

METHODS AND ANALYSIS

The protocol for this review has been developed in accordance with the Cochrane Back Review Group guidelines, the Cochrane Handbook, and the PRISMA-P preferred reporting guidelines (see online supplementary file 1).[25–28] This protocol has been registered on PROSPERO (CRD42019125156) on the 12/02/2019.

Eligibility criteria

The PICOS framework has been used to inform the eligibility criteria for the inclusion and exclusion of studies.[28 29]

Population

The population of interest is adults (aged 18 years or older) with chronic, non-specific (with no diagnosable underlying pathology) LBP, or adults who are pain-free and included in the context of a comparative control. For the purpose of this review, the definition for chronicity in LBP will follow the minimum guidelines by Dionne *et al*, and include pain in the lower back which has persisted for more than 3 months.[30]

Intervention/Exposure

The intervention of interest is the use of surface EMG to measure the level of activity of the lumbar musculature. This will include any measure of activity in any lumbar paraspinal muscle which can be (or has been) measured by surface EMG, including, but not limited to, the lumbar erector spinae or any of its component parts and the lumbar multifidus.[8 31 32]

Comparison

Studies must include a comparison of muscle activity related to a functional task. This comparison could be within-groups or between-groups and could include pre-task and post-task measures; continuous or multiple measurements throughout a task; or associated with a change in symptoms.[33]

Outcomes

The outcome of interest is the measurement of the amplitude of lumbar paraspinal muscle activity. Any measure related to the amplitude of muscle activity will be included, including root mean square (RMS), average rectified

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Table 1 Summary of Inclusion and exclusion criteria

Inclusion criteria	
Population	Adults (>18 y), men and women with CNSLBP or a pain-free control
Intervention/Exposure	Use of surface EMG to measure the amplitude of activity of the lumbar paraspinal musculature
Comparison	Differences in the magnitude of lumbar muscle activity between individuals with CNSLBP and pain-free controls
Outcomes	Surface EMG measurement of the amplitude of muscle activity
Study Type	Quantitative observational studies
Exclusion Criteria	
Population	Studies where individuals under the age of 18 were explicitly included Individuals with LBP defined by study authors as 'Chronic' but has not persisted for over 3 months Individuals with CNSLBP who have been diagnosed with an underlying pathology
Intervention/Exposure	Results from the use of intramuscular EMG in tandem with surface EMG
Study Type	To reduce the risk of the introduction of bias, studies of all languages will be included in the search, however due to limitations in time and resources, studies not in English will be excluded but noted on the PRISMA flow diagram.

value (ARV) and area under the curve (integrated EMG) in both absolute values (voltage) and relative to reference contractions including maximal, submaximal or reference voluntary contractions (MVC, SMVC, RVC respectively).[34] Only studies which measure the level of activity of the muscle quantitatively will be included.

Studies

From scoping searches, it was determined that the highest level of evidence for this review is likely to comprise of observational studies.

The inclusion and exclusion criteria for this review are briefly summarised in table 1.

Information sources

Information sources will be searched from inception to 21 August 2019. Specific search strategies using medical subject heading (MESH) terms have been developed to use where appropriate. The following databases will be used for searching: Web of Science, PubMed, MEDLINE (OVID Interface), EMBASE (OVID interface), ZETOC and CINAHL (EBSCO interface).

Hand searching of key journals will be conducted, including the Journal of Electromyography and Kinesiology, Clinical Neurophysiology, Muscle & Nerve, Clinical Biomechanics and The Clinical Journal of Pain. Notable authors in the field will be contacted to identify relevant unpublished literature which is currently in preparation. Grey literature will be included in the search, and searches will be conducted using the British National bibliography for report literature, Opengrey and dissertation abstracts. Conference proceedings from 2017 to 2019 will be accessed, including the Congress of the International Society of Electrophysiology and Kinesiology (ISEK), the World Congress of Biomechanics (WCB), Society for Back Pain Research Annual Meeting (SBPR) and the World Congress on Low Back & Pelvic Girdle Pain. To ensure completeness of the literature search, the reference lists of studies which are identified as eligible following the search will be hand searched to ensure that no relevant studies are missed.

Search strategy

The search will be conducted by the lead author (AS) and has been informed by subject-specific expertise and the completion of scoping searches. There will be no restrictions on the search in terms of the design, language, region or date. The keyword search strategy has been developed for MEDLINE (OVID interface) and incudes MESH keywords to ensure completeness of the search. The specific search terms will be modified to reflect differences in keywords and syntax between databases; however, the search strategy will remain consistent. A detailed search strategy for the Medline database has been included in online supplementary file 2.

The lead author will search all information sources to identify relevant studies, and subsequently remove all duplicate studies. Then two authors (AS, AG) will independently screen the identified studies. Following the identification of all eligible studies, information extraction will be completed by AS, with accuracy checked by AG. The reviewers will not be blinded towards the authors, research group, or institutional information of the studies.

Data management

The results of the literature search, including the citation and abstract for each relevant study will be imported into EndNote X9 (Clarivate Analytics). Studies will be imported during the search, and duplicate studies will be identified and removed prior to the screening process. At this point, the remaining studies will be replicated into

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an individual folder for each reviewer for screening. In order to screen effectively, the full text for all potentially eligible studies will be retrieved and stored in EndNote X9. Screening will be accomplished using forms which have been developed to reflect the previously stated inclusion and exclusion criteria.

Selection process

The study selection process has been designed to reflect the best practice guidelines suggested by the Cochrane Back Review Group.[25] Initial screening of search results will exclude studies in which it is clear from the title and abstract that the content is not relevant to objectives of this review. Where eligibility is unclear, the reviewers will read the full text of the article and use the screening tool to assess inclusion. The screening form will be used to objectively assess the study based on the inclusion and exclusion criteria. This form will identify studies as eligible, ineligible or unclear in terms of its inclusion in the review. In the event that a study is identified as unclear it will be discussed with the second reviewer to determine eligibility. If there is no consensus following this discussion, a third reviewer will be asked to determine the eligibility of the study. Furthermore, in the instance that one reviewer is an author on a potentially eligible study, screening for inclusion will be conducted by the remaining and third reviewer.

Data collection process

Data will be extracted by AS using a standardised form which has been created, based on the Cochrane data extraction template, using the objectives of the review and the inclusion criteria as a guide.[26] The extracted data will be reviewed for accuracy by AG and any discrepancies discussed between reviewers, where resolution cannot be achieved, the third reviewer will determine which data are relevant. The standardised form will be piloted for completeness of data extraction on a subsection of studies and any necessary changes will be implemented prior to extraction from all eligible studies.

Data items

A summary of data items to be extracted from eligible studies is included in table 2. Where data are missing from studies or the results are presented in an ambiguous way, the corresponding author will be contacted for clarification. If the clarification affects the eligibility of the study, and the author does not respond within a set timeframe, the study will be considered ineligible; however, it will be noted as excluded for ambiguity. If a study appears to use the same sample as another eligible study, the authors will be contacted to ensure that the results are not recorded in duplicate. In the instance that intramuscular EMG has been used in tandem with sEMG, the data from the intramuscular electrodes will be discarded, but the sEMG data will be preserved.

Risk of bias

Bias within individual studies will be assessed independently by each reviewer (AS, AG) with the Newcastle-Ottawa scale (NOS).[35] The scale is designed for use within all types of observational studies and considers the selection and comparability of the sample as well as the assessment of the outcomes.[36] Each study will be designated a star rating from 0 to a maximum of 9 stars, for which guidelines exist to convert to Agency for Healthcare Research and Quality standards.[35 37] Using these guidelines, studies selected for inclusion into the review will be graded as 'Good', 'Fair' or 'Poor' quality with the star ratings for each subheading also reported.

Previous investigations into the reliability and the validity of NOS have presented mixed results, showing in some cases lower reliability when compared with other tools.[36 38 39] However, it has previously been reported that for observational studies 86 individual risk of bias tools have been created, with no clear preferable candidate for determining risk of bias.[40] For this review, it was decided to follow the advice of Hootman and colleagues, who determined that the NOS remains preferable to alternate risk of bias tools due to its moderate to high reliability, ease of use and face validity across observational designs.[36]

Table 2 Summary of items to be extracted from eligible studies using the standardised data extraction form

Information area	Data extracted
Background	Authors Year of Publication Title
Methodology	Study Design Setting Sample Characteristics (Sample size, age, anthropomorphic data) LBP Characteristics (Duration, average pain, current pain, laterality) Task Information (Fatiguing, endurance, repeated, standing, length of recording, etc) Type of surface EMG (bipolar, linear array, HDEMG) EMG Processing (sampling frequency, filtering, offline processing) EMG Processing of signal amplitude (RMS, ARV, integrated EMG) Muscles measured Absolute or Normalised Activity values Normalisation Parameter and technique (MVC, SMVC, RVC)
Results	Amplitude Outcomes (Within subjects Pre/Post, between subjects pre/post, changes throughout, systematic differences between groups) Effect Sizes where reported

Data synthesis

In order to be included in meta-analysis, the outcomes and the methodology of the considered studies must be homogenous; as such, the possibilities for meta-analysis will become clear following data extraction. Thus, the

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remainder of this section speculates on the expected search results; however, changes may be required following data extraction.

The heterogeneity of the eligible studies will be assessed using the following characteristics:

- Type of sEMG used
- Measurement of muscle activity outcome (eg, is the measurement relative or absolute)
- Which muscles were considered
- Task completed (eg, fatiguing, endurance, repeated, standing)

Where homogeneity is sufficient between groups within these categories, then inclusion within meta-analysis either as a large group or as several subgroups will be determined by both reviewers. If the included studies are clearly homogenous in methodology, or are not clearly heterogeneous, then each reviewer will independently place studies into appropriate groups for analysis. This grouping will be determined by each reviewer independently, based on factors that they believe will allow the best and most accurate comparisons to be made. Thus, these subgroupings are likely to be based on the methodological factors mentioned previously, for example, task completed and/or muscles considered, as appropriate for the eligible studies. If appropriate, reviewers can include studies in more than one subgroup (eg, one group for muscles and one group for task), however in this instance care will be taken to ensure that these subgroups are not included in the same meta-analysis. Where concurrence exists between reviewers for these groupings, meta-analysis will occur. If the reviewers do not broadly agree on groupings then the potential for meta-synthesis will be instead discussed by the reviewers. Where disagreement occurs at any stage that cannot be resolved by the primary reviewers, the third reviewer will determine the possibility of meta-analysis or meta-synthesis.

In the instance that the reviewers determine a meta-analysis is appropriate, a statistical test of heterogeneity will be performed, providing an I^2 value for the heterogeneity of the sample.[41] The I^2 value will be reported as a percentage and interpreted as suggested by the Cochrane Handbook for Systematic Reviews of Interventions.[26] Significance in the measure of heterogeneity as calculated by the chi-squared test, will be set at $p<0.1$. As in previous reviews, the groupings of studies will be eligible for meta-analysis if an I^2 value of <50% (low heterogeneity) is calculated.[42] Groups which exceed this value will be ineligible for meta-analysis and so will instead be considered for meta-synthesis.

Comparisons of changes in muscle activity between studies may be very difficult to assess due to differences in signal processing, tasks and experimental design. However, where meta-analysis is determined to be appropriate, results will be extracted from the relevant studies and compiled, with changes normalised and reported as percentage changes in all studies. Where inadequate data are provided within the publication to allow this analysis, the authors will be contacted to provide further data. This compiled data will then be used to create Odds Ratios (ORs) investigating the relationship between LBP and changes in muscle activity across studies.

ORs are traditionally used for binary outcomes whereby the odds of one outcome or another can be easily compared.[43] Thus, if appropriate for the studies identified within the review, here, it is suggested instead to use the ORs to allow comparisons between different subgroupings of tasks and muscles. ORs will be calculated from the proportions of studies within each subgroup to show either an increase or a decrease in the level of activity. This analysis will allow for the estimation of effects across tasks and muscles, and will indicate if any specific tasks or muscles have outlying results. Within subgroups, percentage changes in activity will be correlated with secondary outcomes, including the level and duration of pain, if reported, to investigate the what effect these have on lumbar muscle activity.

If the data are not sufficiently homogenous, a narrative synthesis will instead be applied to the data set, with more binary elements of analysis also included. The results will be distilled to provide results in the format of an 'increase', 'decrease' or 'no change' in activity in the muscle activity.

Confidence in cumulative evidence

The risk of publication bias will be assessed by conducting a detailed search of unpublished studies, contacting notable authors in the field and the inclusion of grey literature in the search. Relevant conference proceedings from the previous 2 years will be accessed and authors of presented studies which were not brought forward to publication will be contacted.

The pooled data will be assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach to evaluate the overall quality of the literature.[44] GRADE approach will be applied to the groupings identified earlier, and will be carried out according to the guidelines. Thus, observational studies will initially be given a 'Low' rating for the quality of evidence, and then the quality of evidence can be either upgraded or downgraded from this point.[45] Studies will be upgraded for factors such as large effect sizes or dose–response relationships between LBP severity and activity. Studies could also be downgraded for factors including publication bias, indirect relationships with results or inconsistencies between studies.[44 45] Following this process, a final quality level will be given to the evidence, and will be either 'High', 'Moderate', 'Low' or 'Very Low' which can be interpreted in line with the GRADE guidance.[25 44 45]

Patient and public involvement

The topic of this review was discussed at our established patient and public involvement meetings. Patients will not be involved in the analysis and data collection of the systematic review.

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Ethics and dissemination of results

No ethical approval is required for this review, as it will only involve the collation of previously published literature. This systematic review will collect and collate results from the numerous studies which have investigated changes in superficial lumbar muscle activity in people with CNSLBP. While heterogeneity is expected, it is expected that this review will succeed in identifying common adaptations which may be muscle and task specific. Consequently, the results of this review, and any differences in muscle activity between individuals with and without LBP, have the potential to influence future research into LBP including potential rehabilitation approaches. The results of this review will be submitted for publication in a peer-reviewed journal and presented at conferences.

Contributors All authors contributed to the focus of the systematic review topic. AS drafted the initial protocol, with guidance and feedback at all stages from DF, EMV, AG, NRH and ABR. All authors have revised and reviewed each draft of the protocol and have approved the final manuscript.

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Appendix 3 – Sanderson et al., 2019c

Journal of Anatomy

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Variation in the spatial distribution of erector spinae activity during a lumbar endurance task in people with low back pain

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Abstract

This study aimed to investigate the spatial distribution and redistribution of lumbar erector spinae (ES) activity during a lumbar extension endurance task in pain-free participants and how this is modified in people with low back pain (LBP). High density surface electromyography (HDEMG) was recorded using 13 × 5 electrode grids placed over the lumbar ES in 13 LBP and 13 control participants while completing an Ito test to task failure. The root mean square of the HDEMG signals was computed, a topographical map of the EMG amplitude generated and the centre of the activity (centroid) determined throughout the task. The centroid of the EMG amplitude map was systematically more cranial (F 6.09, P 0.022) for the LBP participants compared with the control subjects. Regression analysis showed that the extent of redistribution of ES activity was associated with longer endurance. These results show that LBP participants utilised a different motor strategy to perform the endurance task, characterised by greater activation of more cranial regions of the ES and less redistribution of ES activity throughout the task. This study provides new insight into the functional activation of the lumbar ES and how it is modified when people have pain.

Key words: erector spinae; functional muscle activity; high density EMG; Ito test.

Introduction

Previous anatomical and biomechanical research on the lumbar erector spinae (ES) has focused on the relations and the structure of different portions of this muscle group (Bogduk, 1980, 2005; Christophy et al. 2012). Bogduk (2005), via several dissection studies, described the origins, insertions and functions of the portions of the lumbar ES, work which was adapted by Christophy and colleagues to produce a biomechanical model of the lumbar musculature (Bogduk, 1980; Christophy et al. 2012). These descriptions concurred that although the portions of the muscle group have different origins and insertions, all play important roles in extending the lumbar spine during functional movements. The structures described for the portions of the ES indicate a broad bilateral muscular region lateral to the lumbar spine extending from L5 into the thoracic region (Bogduk, 2005; Christophy et al. 2012). To extend the lumbar spine, the most effective motor strategy would be to recruit fibres especially from the caudal portions of the ES, creating a longer lever arm and conferring a biomechanical advantage to the movement (Bogduk, 2005).

Surface electromyography (EMG) is used to measure muscle activity and can be applied as a means to understand variations in neuromuscular control in individuals with musculoskeletal pain (Fabian et al. 2005; Gallina et al. 2011; Abboud et al. 2014; Falla et al. 2014, 2017; Gizzi et al. 2015). More recent studies have utilised high-density surface electromyography (HDEMG) to understand and quantify changes in the spatial distribution of muscle activity, which was not previously possible with classic bipolar surface EMG. Existing research utilising HDEMG has also commonly evaluated changes in the distribution of muscle activity during either sustained or dynamic contractions by quantifying a shift in the centroid of the HDEMG amplitude map, the point which defines the barycentre of muscle activation (Madeleine et al. 2006; Farina et al. 2008; Gallina et al. 2013; Falla et al. 2014, 2017). HDEMG studies on healthy asymptomatic volunteers have shown that the centre of muscle activity shifts during contraction (Falla & Farina, 2008b; Farina et al. 2008; Tucker et al. 2009) and

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that this redistribution of muscle activity has the physiological significance of minimising muscle fatigue and prolonging endurance (Farina et al. 2008; Gallina et al. 2013; Falla et al. 2014), possibly by preventing overload on the muscle fibres active at the beginning of the task.

Previous HDEMG investigations have described an association between endurance time and the redistribution of muscle activity in the trapezius in asymptomatic participants (Farina et al. 2008). More recently, HDEMG was applied to evaluate changes in lumbar ES activity in a low back pain (LBP) population (Abboud et al. 2014). Participants completed a force-matching modified Sørenson test (lifting of the unsupported upper body with the legs affixed to a plinth), resisting a load cell around their shoulders which simulated 30% of their maximum voluntary contraction (MVC). Increased variability in the position of the centroid of the EMG amplitude map was observed in the healthy controls compared with the LBP group.

Despite these observations, the functional relevance of a change in the distribution of muscular activity remains unclear. We hypothesised that people with LBP would engage different regions of the lumbar ES during isometric back extension, reflecting less efficient activation of the ES, and that people with LBP would show less redistribution of ES activity, which would be associated with significantly lower endurance in this group.

Thus, the aim of this study was to investigate the spatial distribution of lumbar ES activity and redistribution of activity during an endurance task in participants with chronic LBP and pain-free controls. Moreover, we evaluate the relationship between the extent of redistribution of activity and endurance time, with the hypothesis that those who display a larger redistribution of activity would be able to sustain the contraction for longer. This study may provide new insight into the functional activation of the lumbar ES and how it is modified when people have pain.

Methods

This study was an observational, cross sectional case control study using a convenience sample of participants from the staff, students and community of the University of Birmingham, UK. Data collection took place in a laboratory within the Centre of Precision Rehabilitation for Spinal Pain, University of Birmingham.

Participants

LBP participants aged 20 55 were recruited via posters and social media accounts related to the University of Birmingham. Due to the nature of the fatiguing task, it was decided that 55 would be the maximum age of participants eligible for this study. Eligibility criteria included non specific LBP which had persisted for at least half the days of the previous 6 months, exceeding the minimum definition for LBP (Dionne et al. 2008). Consistent with previous studies, age and gender matched control participants (CON) were recruited in the same way and were included if they had no history of LBP or lower limb disorders. Exclusion criteria for both groups comprised concurrent systemic issues including rheumatic and neuromuscular disorders, a history of chronic respiratory or neurological problems, spinal deformity or surgery, cardiovascular conditions, pregnancy and healthcare management for LBP in the previous 6 months (a requirement of the University ethics committee). To support a normal distribution for statistical analysis, a planned sample size of 30 participants (15 LBP and 15 CON) was chosen, consistent with previous HDEMG studies comparing symptomatic and asymptomatic participants.

Ethical approval was granted by the University of Birmingham ethics committee (ERN 17 0782). Participants gave written informed consent prior to data collection and all procedures were completed in accordance with the Declaration of Helsinki.

Questionnaires

Prior to testing, participants from both groups were required to complete several questionnaires to gather population statistics, including the level of disability, intensity of pain and current level of activity. Participants were asked to complete the Oswestry Disability Index (ODI), as it has previously been shown to be a reliable measure of disability relating to spinal pain (Fairbank & Pynsent, 2000). The Tampa Scale for Kinesiophobia was used to assess any fear surrounding movement related to pain (Miller et al. 1991). A Pain Numeric Rating Scale (0 10) (PNRS) was used to assess current pain at the time of testing and pain over the prior week (Breivik et al. 2008). Information on the general health of participants at the time of testing was collected using the RAND 36 item health survey, which has been shown to be effective and reliable as a measure of health across cultures and gender (Hays et al. 1993; VanderZee et al. 1996). Throughout the endurance task (see below), the rate of perceived exertion (RPE) was recorded at 30 s intervals and immediately following task failure using the Borg RPE scale (Borg, 1998). This measure was used to assess the perceived exertion of the participants throughout the task and ensure that the task was appropriate for LBP participants.

Experimental set-up

Surface EMG signals were recorded from the lumbar ES using 13 $\times$ 5 semi disposable 2D electrode grids (OT Bioelettronica, Turin, Italy). Electrodes with a 3 mm diameter were spaced evenly at an 8 mm inter electrode distance; one corner electrode was missing in each grid to provide directional reference. Electrodes were positioned over the lumbar ES on the right hand side in control participants and the most painful side in the LBP group. Where equal pain was reported bilaterally, participants were randomly allocated a side.

Prior to the application of electrodes, the skin in the region lateral to the lumbar spine was prepared by shaving the area if needed and then applying an abrasive paste (SPES Medica, Italy), and finally washing and drying the region. The electrodes were prepared by applying a thin custom double sided adhesive foam pad to the electrode grid (SPES Medica, Genoa, Italy). The cavities of the electrode grids were then filled with an electroconductive paste (SPES Medica). As there is no way of differentiating different portions of the ES *in vivo*, the electrode was placed on the ES in accordance with EMG guidelines and previous studies (Barbero et al. 2012; Falla et al. 2014). The grids were applied to the skin approximately 2 cm lateral to the lumbar spinous processes, starting at the

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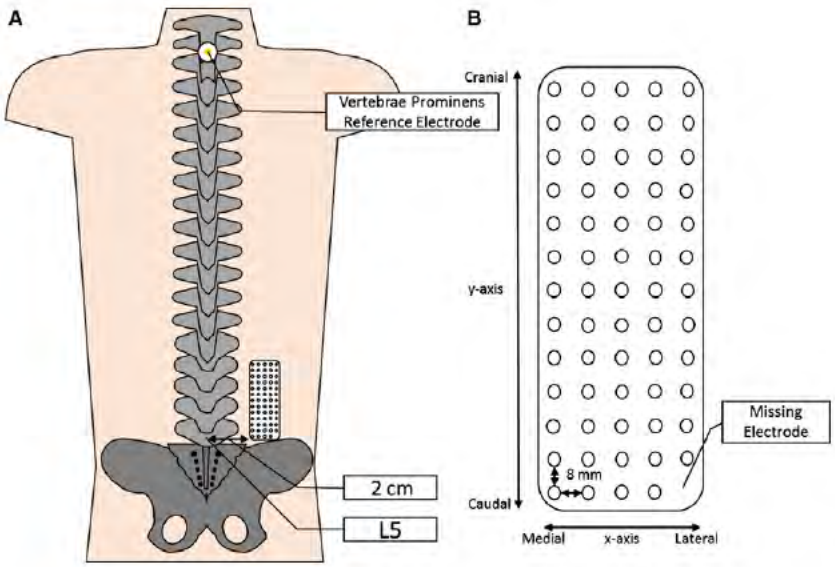


Fig. 1 Depicting (A) the approximate positioning of the HDEMG grid 2 cm lateral to the L5 spinous process on the lumbar ES of the participant and (B) a schematic of the electrode grid showing the *x* and *y* axes, reference electrode and inter electrode distance (not to scale).

level of the L5 and extending to approximately the level of L3, as described previously (Falla et al. 2014). Reference electrodes were placed on prepared skin over the right anterior superior iliac spine and on the spinous process of the vertebra prominens (Fig. 1).

A twin axis SG150B digital goniometer (Biometrics Ltd., Gwent, UK) was applied to the right mid axillary line of the participant. Only one axis (sagittal plane) was used for analysis. The lower sen sor was attached to the centre of the iliac crest, with the midline of the sensor in line with the greater trochanter of the femur. With the participant positioned prone on the plinth, the resting angle was cal brated as 0°, with trunk deviation measured from this point. EMG signals and angular data were sampled at 2048 Hz and ampli fied (400 channel EMG amplifier Quattrocento, OT Bioelettronica; −3 dB, bandwidth 10 500 Hz) by a factor of 150 and converted to digital form by a 16 bit analogue to digital converter. Collected sig nals were stored on a computer hard drive and later analysed using a custom code on MATLAB (The Mathworks Inc., USA).

As described previously by Falla et al. (2014), each grid of elec trodes recorded 64 monopolar signals. These signals were then pro cessed offline to form horizontal derivatives across the grids. This was achieved by filtering the monopolar signals using a 20 350 Hz band pass filter and then processing adjacent signals to produce 59 bipolar EMG signals. The amplitude (RMS) and mean spectral power frequency (MNF) for each b polar derivation were then calculated. The individual RMS and MNF values for each bipolar signal were averaged to produce the mean RMS and MNF values across the grid. The RMS values for each bipolar signal were used to create a topographical map of ES activity. This map was used to determine the location of the *x* and *y* coordinates of the centroid as described previously (Madeleine et al. 2006; Farina et al. 2008; Tucker et al. 2009; Abboud et al. 2014; Falla et al. 2014, 2017). The location of the centroid was averaged across the 10 s and 10% epochs for fur ther use in analysis.

The values for the *x* and *y* coordinates of the centroid were anal ysed as an absolute shift in mm from the start point quantified in the first 10% epoch (Falla et al. 2014). As movement of the centroid was both cranial and caudal in both groups, to allow for compar ison between groups of the absolute shift in the *y* coordinate of the centroid, both positive and negative movements were made positive.

Experimental procedure

To complete the endurance task, participants were required to maintain an Ito test, as described by Ito et al. (1996) and Muller et al. (2010), until task failure or until 300 s. Participants were first asked to lie prone on a plinth, with a firm semi circular foam pad (18 cm diameter) centred below the anterior superior iliac spines. To complete the endurance task, participants were asked to lift their sternum from the plinth, raising their upper body by ~15°. While maintaining this position, partic pants were asked to keep their arms in line with the body axis and not in contact with the plinth; participants were also required to contract their gluteal mus cles and retain a neutral neck position. Prior to beginning the task, an investigator demonstrated the correct position for completion of the Ito test, and participants were permitted to complete a short 5 s contraction to ensure they had the correct technique.

Throughout the task, the angle of the body axis was monitored visually and participants were alerted if their body axis was approaching the upper or lower acceptable limits (± 10°; Demoulin et al. 2007). Task failure was determined by a drop in the angle of trunk of greater than 10° at any point. While completing the con traction, participants were timed using a stopwatch; the time was recorded until task failure or until the maximum contraction dura tion was reached (300 s). Throughout the task, participants were given verbal encouragement and at 30 s increments were provided with feedback on how long they had sustained the contraction.

Statistical analysis

Statistical analysis was performed using SPSS 24 (IBM, USA) with an alpha level set at 0.05. Regression analysis and analysis of covariance (ANCOVA) tests were performed using PRISM (GraphPad, USA). Where *P* values were reported on SPSS as 0.000, they are here given as $P < 0.001$. Effect sizes have been reported where appropriate with

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ANOVA results, based on guidance by Lakens (2013) in the format of generalised η^2 (η_g^2), alongside η^2 values. For interpretation of these values, effect sizes are defined as small (η^2/η_g^2 0.01), medium (η^2/η_g^2 0.06) or large (η^2/η_g^2 0.14) (Cohen, 1988; Lakens, 2013).

A Student *t* test was performed to identify any differences in endurance t mes between groups. The questionnaires used to gather sample characteristics were interpreted according to their respective guidelines (Miller et al. 1991; Hays et al. 1993; Fairbank & Pynsent, 2000; Childs et al. 2005). Student *t* tests were performed for each group to identify differences between the samples at base line. To determine whether the failure of the task was influenced by fear of movement, the endurance time for each participant was correlated to their respective TSK score.

No direct comparison of the values reported for perceived exer tion could be made between groups, as the time to task failure var ied between groups. Therefore, the initial value after 30 s, the value at the mid point of endurance, and the level of exertion at task failure were determined for each participant. Significant differ ences between groups were investigated using a repeated measures analysis of variance (ANOVA).

To make comparisons between groups with different times to task failure, the total contraction time for each participant was nor malised into 10% epochs of the total endurance time (Farina et al. 2008). Repeated measures ANOVA, with factors of group (CON and LBP) and time (10 epochs), was used to compare differences in EMG variables between groups. Newman Keuls post hoc tests were also conducted where appropriate.

To identify trends in the displacement of the *y* coordinate of the centroid between groups, a linear regression was performed. To ensure that the results were not affected by the normalisation of time, this regression was performed using absolute endurance times and *y* coordinate displacement values calculated from the position of the centroid in the first 10 s epoch. The regression lines for the CON and LBP groups were compared for statistical significance using an ANCOVA.

Finally, to assess myoelectric manifestations of muscle fatigue, lin ear regressions were performed on RMS and MNF variables (Lari vière et al. 2002). For each participant, the relations between RMS and time to task failure, and MNF and time to task failure were computed. In this analysis, both absolute values for RMS and MNF across time, and normalised values (using the using the first 10 s epoch as a reference) were considered and the resulting slopes extracted. Independent samples *t* tests were then performed on the slopes for each condition to identify the mean slope for each group and identify any differences between these means (Roy et al. 1995; Pagé & Descarreaux, 2012).

Results

Participants

In all, 13 LBP and 13 CON participants successfully completed data collection; population characteristics are reported in Table 1. No significant anthropometric differences were found between groups for body mass index (BMI), height or weight and the BMI for both groups was within the 'normal weight' range (Stenholm et al. 2017). However, as anticipated, the LBP group presented with higher levels of disability (ODI −13.16%) and lower general and emotional health (RAND 36-item health survey). Prior to data collection, LBP participants reported a current pain level of 1.92 out of 10, but a usual pain of 2.92, characterising the pain within the group as mild or low severity (Breivik et al. 2008). No significant correlation was found between scores on the TSK and the endurance time ($R = -0.281$, $P = 0.165$).

Table 1 Mean participant characteristics separated by group, showing the standard deviation where appropriate.

Characteristic	LBP	Control	*P* value
Age (years)	27.39 ± 9.7	26.46 ± 5.0	
Gender (# males)	6	7	
Height (cm)	168.75 ± 9.7	170.38 ± 6.7	
Weight (kg)	70.97 ± 12.4	69.11 ± 12.7	
BMI	24.78	23.78	
ODI (%)*	13.16% ± 8%	0.00%	< 0.001
TSK	25.31 ± 4.89	22.31 ± 7.20	
PNRS			
Current pain*	1.92 ± 1.44	0	< 0.001
Usual pain*	2.92 ± 1.98	0	< 0.001
RAND 36 item health survey			
Physical functioning*	82.52 ± 10.64	99.30 ± 2.52	< 0.001
Emotional wellbeing*	69.85 ± 17.33	82.46 ± 7.58	0.024
Pain*	68.46 ± 16.79	95.00 ± 8.6	< 0.001
General health*	64.62 ± 20.15	82.31 ± 10.53	0.010

Where significant differences occur, the characteristic is marked with an asterisk and a *P* value is displayed.

Endurance

Significantly lower endurance times were recorded for the LBP group ($F = 8.4$, $P < 0.001$) than for the control group (186.3 ± 72.3 s and 283.0 ± 33.0 s, respectively). With a 96.7-s difference, this equates to the LBP group maintaining the contraction for 65.8% of the total time for the CON group on average. The mean values for initial, middle and final perceived exertion are shown in Fig. 2. No significant differences in exertion were found between the groups at any point ($F = 1.42$, $P = 0.216$).

Electromyographical changes

EMG amplitude and mean frequency

Across the duration of the contraction, the RMS was found to be systematically higher for CON than for LBP participants (main effect of group; $F = 6.09$, $P = 0.022$, $\eta_g^2 = 0.18$, $\eta^2 = 0.18$; Fig. 3). This higher activation of the ES was visible in the topographical maps of the EMG amplitude (Fig. 4). On average, the CON participants showed a larger distribution of the activity throughout the entire muscle, whereas LBP participants showed a less diffused activation which tended to be more cranial. When this was quantified, an

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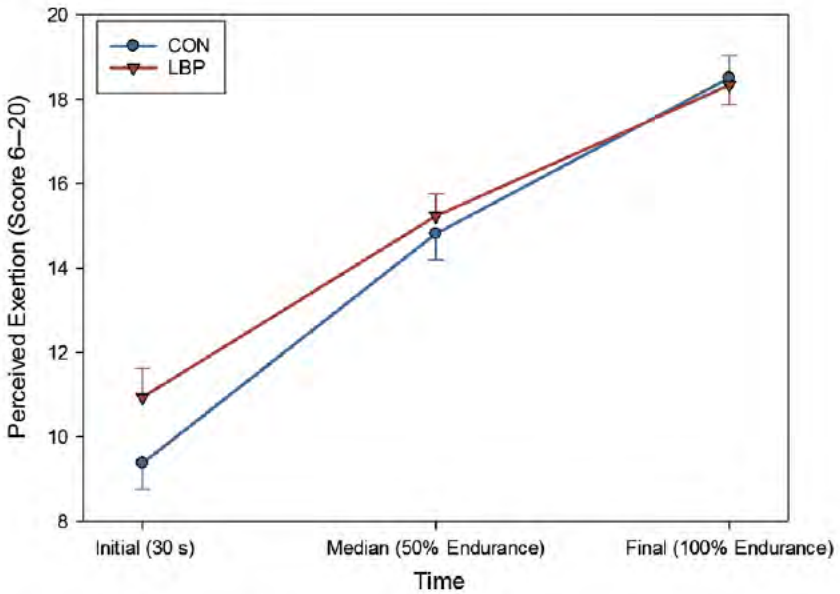


Fig. 2 The mean values for the initial, mid point and final values (and SE) for the RPE as reported by participants during the endurance task. No significant differences were found between groups for exertion during the task.

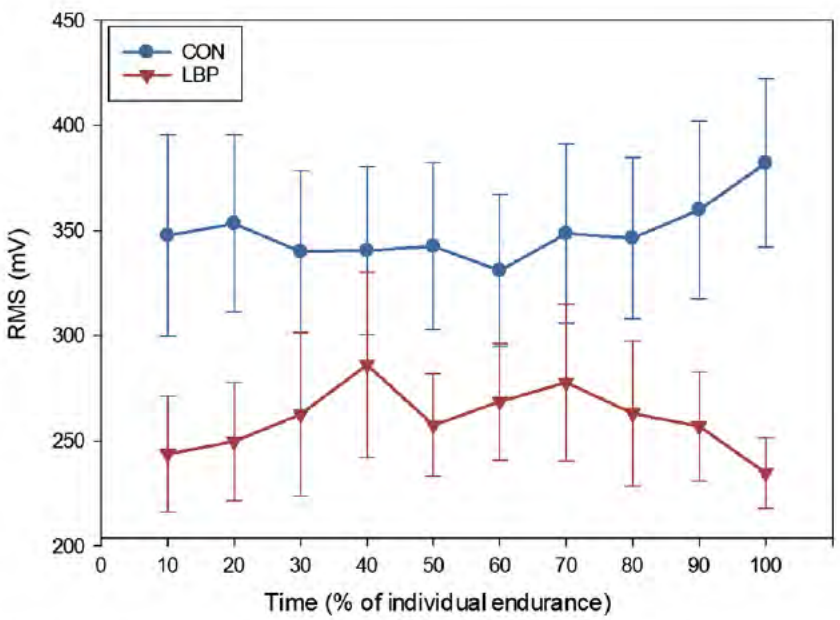


Fig. 3 Average RMS values for LBP and CON participants across the duration of the endurance contractions (and SE), shown in 10% epochs of the participants' total endurance times. No interactions or differences in shift were found between groups, but the CON group was found to be systematically higher throughout the contraction.

even distribution across the entire grid was observed in eleven CON and four LBP participants. Distribution was weighted cranially in one CON and eight LBP participants, and distribution was focused in the middle of the grid for one Con and one LBP participant.

There were no significant differences between groups for the change in RMS throughout the task ($F = 1.42$, $P = 0.216$). There were also no significant increases or decreases in the mean RMS recorded for either group at any point during the endurance task ($F = 0.929$, $P = 0.344$). No significant differences between groups were observed for the mean MNF at any point during the contraction ($F = 1.118$, $P = 0.334$).

Centroid of the EMG RMS map

No significant differences were found between groups for the position of the *x*-coordinate of the centroid (medial-lateral direction) throughout the task (initial position $F = 2.27$,

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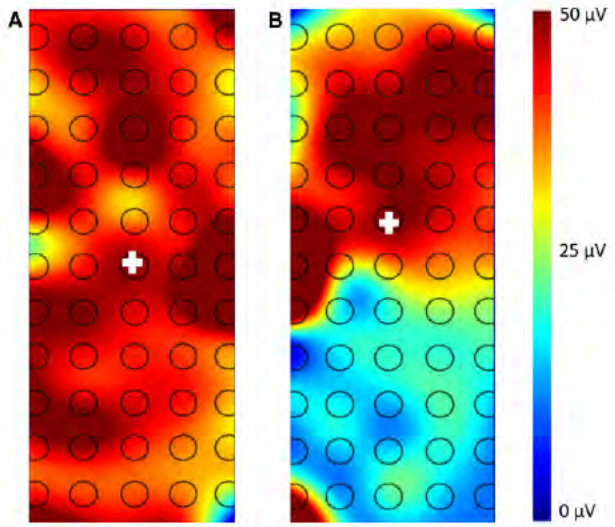


Fig. 4 Representative RMS topographical maps for CON (A) and LBP (B) participants during the endurance task. The centroid is depicted by the crosshair and the scale is indicated in μV.

$P = 0.77$; shift over the duration of the contraction $F = 2.27$, $P = 0.77$).

The *y*-coordinate of the centroid (cranial-caudal direction) in CON participants was found to be systematically more caudal than in the LBP group (main effect for group $F = 44.00$, $P < 0.001$, $\eta_g^2 = 0.64$, $\eta^2 = 0.65$). The *y*-coordinate was found to be approximately 42.0 mm (± 4.99 mm) cranial of the reference electrode in CON participants, but approximately 53.6 mm (± 3.64 mm) cranial of the reference electrode in the LBP participants. Throughout the endurance task, there was a mean difference between the LBP and CON in the *y*-coordinate position of 11.6 mm (Fig. 5).

Using the location of the *y*-coordinate of the centroid in the 1st epoch as a reference point, the displacement was calculated for each 10% epoch. To achieve this, the shift in mm was measured from the position of the *y*-coordinate in the 1st epoch; this was either a positive (cranial movement) or a negative (caudal) value. No clear direction of shift was found (cranially or caudally), as groups showed both cranial and caudal movements (CON six cranial, seven caudal; LBP nine cranial, four caudal). To better understand the movement of the centroid, all values for displacement were made positive and therefore net displacement was used for all *y*-coordinate shift results. At task failure, the mean *y*-coordinate displacement for the CON group was 2.10 ± 0.45 mm, whereas for the LBP group it was 1.40 ± 0.29 mm. Both groups showed a significant displacement of the centroid in the *y*-axis over time ($F = 2.5$, $P = 0.004$, $\eta_g^2 = 0.22$, $\eta^2 = 0.30$) and a significant displacement within each group ($F = 9.9$, $P = 0.01$; Fig. 6). There was no interaction between groups for the displacement of the *y*-coordinate in the data which had been normalised to task failure ($F = 1.709$, $P = 0.134$).

The regression analysis performed using absolute values for time showed a significant relationship between the shift in the *y*-coordinate of the centroid and the time to task failure (Fig. 7) for both groups (CON $r^2 = 0.142$, $P < 0.0001$; LBP $r^2 = 0.053$, $P = 0.0004$). Additionally, ANCOVA analysis showed that there was a significant difference between the regression lines for each group ($F = 5.597$, $P = 0.0183$), indicating that the relationship between *y*-coordinate shift and time was significantly different between groups (LBP/CON; Zar, 2010).

Myoelectric manifestations of muscle fatigue showed no differences under any condition. There were no differences in the slopes between groups for absolute RMS ($P = 0.71$), normalised RMS ($P = 0.37$), absolute MNF ($P = 0.48$) or normalised MNF ($P = 0.79$).

Discussion

This is the first study to assess muscle activation behaviour using HDEMG during a functional position-matching lumbar endurance task in people with and without LBP. The results revealed an altered motor control strategy to a standardised endurance task in people with LBP with evidence of activation of more cranial regions of the lumbar ES with respect to asymptomatic people. Moreover, a relationship was also demonstrated between the extent of redistribution of muscle activity and endurance time which has important implications for the understanding of the neurophysiological responses to fatigue, additionally the physiological significance of these findings are supported by large effect sizes.

Distribution of activity

Throughout the endurance contraction, the RMS was found to be significantly higher in the CON group than in the LBP group. One possible explanation for this disparity in amplitude could be quantified from the systematic differences in the position of the centroid along the *y*-axis. Throughout the task, the *y*-coordinate of the centroid for the CON group was 12 mm caudal to that of the LBP group. Previous studies which have induced pain via injection of hypertonic saline, have shown that areas with greater pain show reduced activity, and that in an acute painful condition, the muscle activation can shift outside of the painful region (Madeleine et al. 2006; Falla & Farina, 2008a; Falla et al. 2017). Although somewhat speculative, it is likely that a more caudal centre of contraction could indicate a more biomechanically favourable contraction by activating a greater number of fibres. In this instance, those with pain appear to have shifted the activity in the ES more cranially. A more caudal contraction, which is distributed over a larger area of the muscle, would be able to utilise the larger volume of muscles from lower lumbar vertebrae and spread the load more effectively across a greater number of muscle

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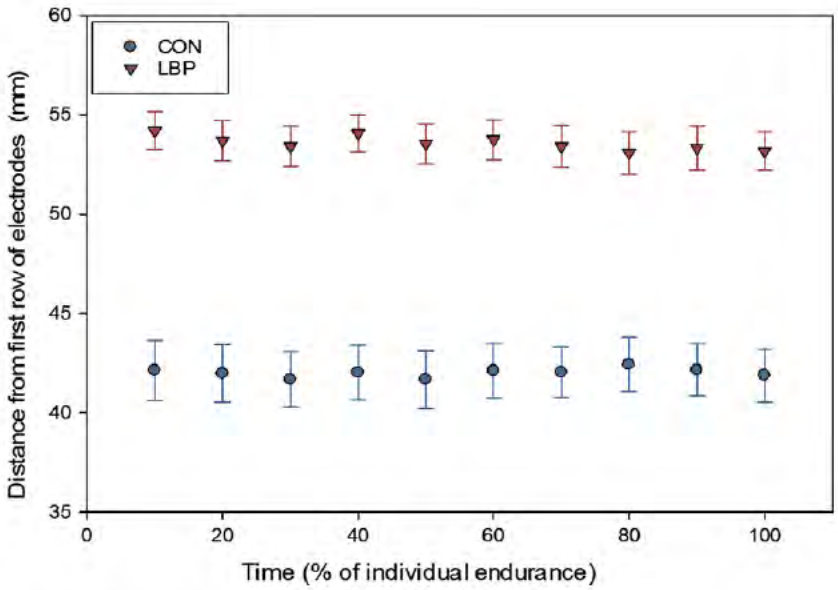


Fig. 5 Absolute mean locations (and standard error, SE) of the *y* coordinate of the centroid for CON and LBP group throughout the endurance contraction.

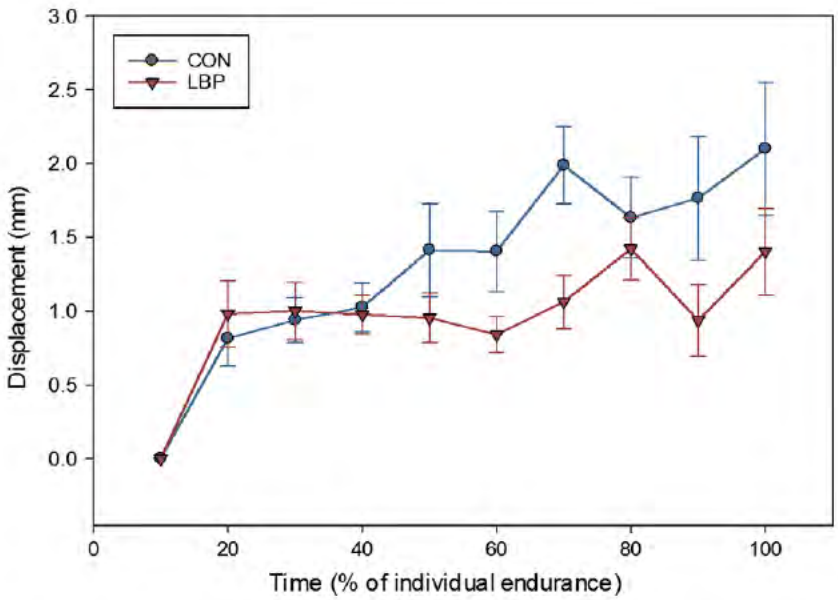


Fig. 6 Displacement of the *y* coordinate of the centroid from the position in the first 10% epoch (and SE), showing a significant displacement of the *y* coordinate for both the CON and the LBP group.

fibres, creating a longer lever arm (Bogduk, 2005). The longer lever arm would act to minimise the force needed to sustain the contraction and the diffuse activation would reduce localised fatigue, facilitating sustained endurance.

Redistribution of lumbar ES activity

During the Ito test, the CON participants showed a greater shift of the centroid of the EMG amplitude map indicating a greater redistribution of lumbar ES activity than the LBP group. It was also shown that the amount of redistribution increased progressively over the duration of the task and that there was an association between the extent of redistribution of activity and endurance time. As previously described by Falla et al. (2014), a redistribution of activity likely prevents localised muscle fatigue through the build-up of metabolic factors and overload on specific regions of the muscle. The task used in Falla et al. (2014) was dynamic and consisted of periodic contractions, whereas the contraction used here is static and so the tissue would be under

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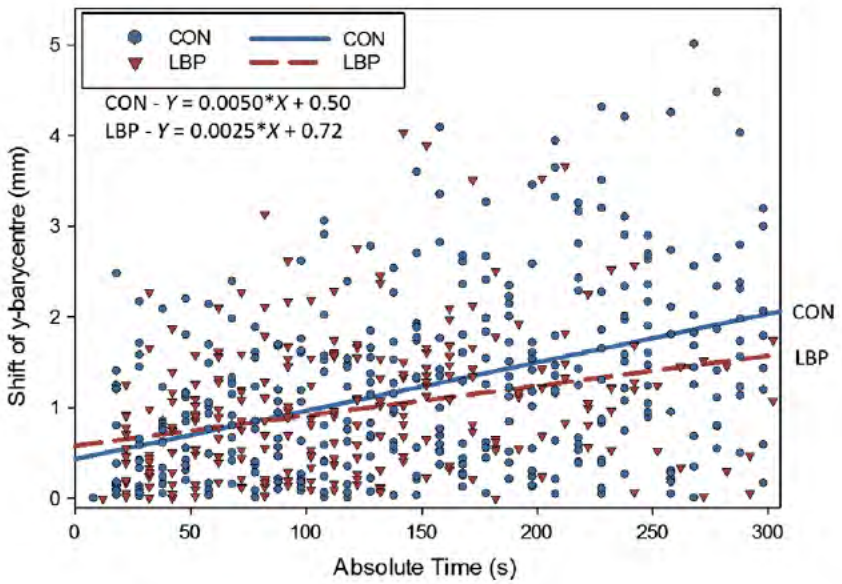


Fig. 7 Linear regression analysis of the shift in *y* coordinate of the centroid, showing significant variation in the shift of the *y* coordinate over the length of the endurance contraction (F 5.597, P 0.0183). Two CON points where shift was more than 6 mm not shown.

further strain due to decreased blood flow and ischaemia (Masuda et al. 1999).

The results of this study do not support a direction of shift for this task, as there was no clear preference for a direction in either group. However, this study differs from previous studies which used HDEMG to examine the lumbar muscles, as it does not involve an external force. Gallina et al. (2013) investigated the significance of the shift in the trapezius muscle and determined that the direction of shift was task-dependent. Russ et al. (2018) and Thomas et al. (2011) showed that there were specific differences in lumbar endurance between force- and position-matching tasks but they were unable to give the reasons for these differences. The lack of a clear direction of shift seen in this study may imply a focus of muscle activity in a more biomechanically favourable point for each participant. As there was no specific point to 'push' against, the centre of activity for each participant was likely determined by individual anthropomorphic features, for example a greater trunk length to leg length ratio. In this study, it is speculated that as participants were not secured to the plinth or pushing against a point, the impact of the relative size and weight of the legs compared with the upper body would impact on the stability of the participant while contracting. Thus the participant might be likely to sustain a contraction which affords them the optimal stability for their individual anthropomorphic characteristics.

Muscular activity

Biomechanical and anatomical models of the lumbar musculature indicate that the shared insertions of portions the ES cause a diagonal slight overlapping of successive superficial fibres (Bogduk, 1980, 2005). According to anatomical studies, the portions of the ES which are likely to be muscular in the region beginning 2 cm lateral to L5 include the *iliocostalis lumborum pars lumborum* and the *iliocostalis lumborum pars thoracis*, with the muscular portions of the longissimus being too medial or too cranial to be covered by the electrode grid. In the *pars lumborum*, the deepest and most lateral fibres are from L5 and the most superficial and medial fibres from L1; each successive lamina of fibres slightly overlaps the previous layer (Bogduk, 2005; Christophy et al. 2012). The Ito test used in this study is designed to achieve relative isolation of the lumbar musculature, so the distribution and redistribution of activity in this portion of the muscle is thought to be key to understanding endurance in this task (Muller et al. 2010). It is therefore suspected and proposed that due to pain in the lumbar region, LBP participants utilised a motor control strategy which preferentially activated different portions of the muscle, such as the more cranial *iliocostalis lumborum pars thoracis* and thus led to a shorter time to task failure compared with the CON group. As no imaging was used in this study, the exact distribution of activity among portions of the ES, and what effect any individual variations in muscle architecture or fibre distribution could have on the activation pattern, remain unknown (Mannion et al. 1997, 2000).

Endurance and fatigue

The LBP group demonstrated endurance which fell significantly short of the CON group. Similar findings have been demonstrated in previous studies investigating lumbar endurance to task failure; however, the absolute endurance

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times reported here were significantly higher than those reported following a Sørenson test (Abboud et al. 2014; Jubany et al. 2017). This difference could be attributed in part to the differences between the force-matching tasks previously used and the position-matching tasks such as one the Ito test used here (Russ et al. 2018). However, Muller et al. (2010) reported lower endurance times for a position-matching Sørenson test when compared directly with an Ito test. In this instance, it may also be relevant to consider the biomechanical and myoelectrical differences between the Ito and Sørenson positions. As discussed previously, muscle activation in the Ito test is focused on the lumbar region, whereas the Sørenson test has shared activation between the lumbar and hip extensors, possibly contributing to differences in endurance time (Muller et al. 2010). Additionally, although both tasks are measures of lumbar endurance, each requires a different position to be held; the Ito test requires spinal extension to be sustained and the Sørenson requires an unsupported neutral spine to be maintained against gravity (Muller et al. 2010). Due to this, it is likely that the point at which the participant's centre of mass is supported may be lower in the Ito test, producing a lower moment.

At task failure, both LBP and CON participants reported a mean RPE of between 18.3 and 18.5, indicating that both groups reached a similar level of exertion. Analysis of the MNF results and the indices measuring the myoelectric manifestations of fatigue revealed that there were no significant differences between the CON and LBP groups. Previous HDEMG studies evaluating fatigue of the lumbar ES have shown greater myoelectric manifestations of fatigue than these results suggest; however, other studies also did not find significant differences between groups (Tucker et al. 2009; Abboud et al. 2014). This could be explained partly by recent studies which have demonstrated that frequency variables, including MNF, do not accurately predict motor unit recruitment during contractions (Merletti & Farina, 2016; Vecchio et al. 2017). Additionally, it has been shown in the knee extensors that myoelectric manifestations of fatigue are only seen when the exertion exceeds 40% of the MVC (de Ruiter et al. 2012). Two exercises in a study by Plamondon et al. (2002) were similar in position and function to the Ito test; in that study, these exercises were found to be between 26 and 32% of a participant's MVC. As the current study did not assess the functional capacity of the participants, the results for MNF may be affected by the task being below 40% of an MVC for some participants.

The results of this study coalesce to indicate that the LBP participants utilise a different motor control strategy to complete the task. This strategy was characterised by a reduced activation of the ES which was focused more cranially and which throughout the task showed less redistribution of activity. It appears that participants used less favourable portions of the ES to complete the task, resulting in shorter endurance times.

Strengths and limitations

A strength of this study was its use of HDEMG to present a more comprehensive characterisation of ES activity during an endurance test, a test which can be easily replicated in a clinical environment. In addition, the Ito test presented here has previously been found to isolate the lumbar musculature better than the Sørenson test does (Muller et al. 2010). No significant differences were found in the RPE between groups, supporting the suitability of the Ito test in this population. However, it should be considered that as no clear guidelines for task failure have been validated for the Ito test, the task failure criteria of $\pm$ 10° could be perceived to affect the redistribution of activity during the task. Nonetheless, as systematic differences were seen between groups for all values related to the RMS, we are confident that the differences between groups are valid, although they could hinder comparisons with other lumbar endurance tasks. To mitigate this effect, where possible, generalised effect sizes have been reported with ANOVA results, which have been interpreted in line with the guidelines suggested by Cohen (1988), and reiterated by Lakens (2013), whereby effect sizes are defined as small ($\eta^2 = 0.01$), medium ($\eta^2 = 0.06$), or large ($\eta^2 = 0.14$). However, it has been suggested that these benchmarks for η^2 may not be as accurate in repeated measures conditions. Therefore, we also included the η_g^2 values, which have been proposed to allow better comparisons between studies (Lakens, 2013).

As participants could not be under current active management by a healthcare professional (a requirement of the University Ethical Committee), the LBP group presented with low levels of current pain and mild disability. Although the sample size was relatively small and the LBP participants presented with relatively mild LBP, significant group differences were revealed; even greater group differences may be expected when testing patients with even greater pain severity or longer pain duration (Mannion et al. 2000; Arendt-Nielsen & Graven-Nielsen, 2008). Finally, synergistic muscles were not covered by the HDEMG grid. This limitation was imposed in an attempt to reduce the effect of crosstalk between overlapping muscles of different architecture which may have confounded the results (Martinez-Valdes et al. 2018). Further studies using mixed methodologies, including intramuscular electrodes and motor unit decomposition, may provide clearer information about individual muscle contributions to this task.

Conclusion

Asymptomatic people display a spatial redistribution of lumbar ES activity during an endurance task and this adaptation is reduced in people with LBP. Moreover, people

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with LBP engage more cranial regions of the lumbar ES during trunk extension, likely reflecting an inefficient motor strategy.

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Conflict of interest

There are no competing interests to declare.

Author contributions

AS, EMV and DF contributed to study conception and design. AS and CM acquired the data. AS, EMV and DF performed the data analysis. All authors contributed to interpretation of the data. Drafting of the manuscript was performed by AS, EMV and DF. All authors participated in revising the manuscript and approving the final submission.

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Appendix 4 – Prisma Checklist

Section/topic	#	Checklist item	Reported on page #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	21
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	22
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	23-25
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS).	25
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	26
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	27, Table 2.1
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	29-30
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	30, Appendix 5
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	31

Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	32
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	32, Table 2.2
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	33-35, Table 2.3
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in means).	38
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	38

Section/topic	#	Checklist item	Reported on page #
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	39-40
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	N/A
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	41, Fig. 2.1
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	46-48, Tables 2.4 and 2.5, Appendix 7
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	51, Table 2.6
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	53-67, Figures and Tables
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	53-61

Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	67, Table 2.10
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	N/A
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	70-74
Limitations	25	Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	74-78
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	78-79
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	N/A

From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed1000097

For more information, visit: www.prisma-statement.org.

Appendix 5 – Detailed Search Strategy

Search Terms

EMG Terms - (*Combine with OR*)

1. exp Electromyography
2. Surface electromyography.mp
3. Electromyo*.mp
4. EMG.mp
5. Surface EMG.mp

6. Bipolar EMG.mp
7. Bipolar Surface EMG.mp
8. Bipolar electromyo*.mp
9. Bipolar Surface electromyo*.mp
10. Bi-polar surface electromyo*.mp

11. High Density Electromyography.mp
12. High Density Surface Electromyography.mp
13. High Density Electromyo*.mp
14. High Density EMG.mp
15. High Density Surface EMG.mp
16. High-Density Electromyography.mp
17. High-Density Surface Electromyography.mp
18. High-Density Electromyo*.mp
19. High-Density EMG.mp
20. High-Density Surface EMG.mp
21. HDEMG.mp

22. Multi-channel EMG.mp
23. Multi-channel Electromyography.mp
24. Multi-channel Electromyo*.mp
25. Multichannel EMG.mp
26. Multichannel Electromyography.mp
27. Multichannel Electromyo*.mp

28. 1-31 (OR)

Activity Terms - (*Combine with OR*)

29. Activation.mp
30. Activity.mp
31. Amplitude.mp
32. RMS.mp
33. ARV.mp

34. Average Rectified Value.mp
35. 33-39 (OR)

Low Back Pain - (*Combine with OR*)

36. exp Low Back Pain
37. Low Back Pain.mp
38. Back pain.mp
39. Lumbar pain.mp
40. Lumbago.mp
41. Lumbar Spine Pain.mp

42. 41-46 (OR)

Anatomy Terms (Supplement LBP terms) - (*Combine with OR*)

43. exp Muscle
44. Myo*.mp
45. Skeletal muscle.mp
46. Musc*.mp
47. Erector Spinae.mp
48. Lumbar Muscle.mp
49. Lumbar Musc*.mp
50. Multifidus.mp
51. Multifidi.mp
52. Iliocostalis.mp
53. Longissimus.mp
54. Spinalis.mp
55. Low Back.mp
56. Lumbar.mp

57. 48-61 (OR)

Overarching Searches

58. 28 AND 35
59. 42 AND 57

60. 58 AND 59

Appendix 6 – Modified Newcastle Ottawa Scale and Justification

Newcastle Ottawa Quality Assessment Scale

Cross-Sectional Studies

Adapted from Newcastle Ottawa Quality Assessment Scale for Case-Control Studies based on elements from the STROBE guidelines and the Newcastle Ottawa Scale manual

Note: A study can be awarded a maximum of one star for each numbered item within the Selection and Exposure categories. A maximum of two stars can be given for Comparability.

Selection

1) Is the case definition adequate?
   a) Yes, with independent validation □
   b) Yes, e.g. record linkage or based on self-reports
   c) No description

2) Representativeness of the cases
   a) Consecutive or obviously representative cases □
   b) Generally representative cases □
   c) Potential for selection biases or not stated

3) Selection of Controls
   a) Community Controls □
   b) Alternative Control recruitment
   c) No Description

4) Definition of Controls
   a) No history of disease □
   b) No mention of history of outcome

Comparability

1) Comparability of cases and controls on the basis of the design or analysis
   a) Study controls for two or more elements of the Population Demographics □□
   b) Study controls for any one element of the population demographics □
   c) Study does not control for any factor

Exposure

1) Description of EMG Exposure
   a) EMG sensor placement, recording equipment and processing are clearly described and standardised □
   b) EMG sensor placement, recording equipment and processing are sufficiently described and standardised □
   c) EMG sensor placement, recording equipment and processing are poorly described

2) Same EMG Exposure for cases and controls

a) yes □

b) no

3) Description of Task Exposure

a) Task was well described and implemented in a standardised well in both groups □

b) Task was well described but not standardised

c) Task was poorly described and standardised

Question Number	Changes	Justification
Section 1	**Minor question wording changes**	
1	No Changes made	This question seeks to identify how the LBP/Con groups have been verified in terms of their symptoms or lack thereof.
2	Addition of a second category	To account for this, an additional category has been added to account for the sample meeting the eligibility criteria and participating, but not being fully representative of the population the study is designed to investigate. An example of this in LBP would be the inclusion of individuals who have low (2/10 on the PNRS) levels of pain for their average pain levels. These individuals might meet the inclusion criteria and so show no sampling bias; however, they do not fully represent the clinical population with consistent high-levels of pain and disability.
3	Modification of second category	The original wording relied on cases being recruited from a hospital or structured recruitment process. The question sought to identify if the only differences between cases and controls was the presence of the case symptoms and both arose from the same community. The second category was identifying if the controls were instead other individuals from the hospital who did not have the case, and so could be from a different background or community). The new wording allows for the high possibility of cases not being recruited from a hospital setting, which would remove the possibility of hospital controls. Instead the category allows for the classification of if the cases and controls were recruited from the same population or if a different sampling method was used for controls which could introduce selection bias.
4	Rewording of second category	This question is assessing if bias could be introduced through the inclusion of individuals who have previously had the case symptoms, if that should be an exclusion criterion. The original wording for this question is focussed on the 'source' of the case symptom, however this is not relevant to the studies in this review.

		The question seeks to assess if controls should never have had the symptoms previously or if this is not the case, so the wording has been altered to ask this question more specifically. The new wording is copied from the original manual for coding this question in the NOS for case-control studies, therefore ensuring that the essence of the question is maintained.
Section 2	**Minor Alterations**	
5	A third category has been included and specific factors have been included.	The original question assesses how well cases and controls can be compared and if matching was introduced in the design stage. The design left space for individual reviewers to select factors which were most important to their review. In this instance, population demographics have been selected as the factor to control for, as EMG (the primary outcome) could be affected by anthropomorphic features. The coding manual suggests that if these criteria are not met or if groups are comparable by coincidence after the fact, then no stars should be allotted for this section, however the original format did not leave an option for this. In this modification this additional category has been added so as to ensure that this question is answered and no stars are intentionally given, rather than the question accidentally left blank through error.
Section 3	**Major Changes**	**Questions in this section have required the most modifications as the original section sought to ascertain if the cases and controls were exposed to the variable of interest. In studies included here, the variable of interest is the EMG activity and by participating in the experiment, it is known that cases and controls are exposed.**
6	This question has been specifically re-written for the EMG exposure.	The original question assessed the possibility of bias being introduced through the accidental inclusion of individuals as cases who have not been exposed to the variable of interest. This would be important in following the progression of individuals with, for example, vertebral fractures longitudinally as the process of proving, or indeed not proving, that a fracture has occurred is a potential source of bias.

		However, in this review, there are two exposures, one to LBP and one to the EMG and task. Exposure to non-specific LBP is not externally verifiable as it is an 'invisible disability' so all included studies would be ranked as 'self-report'. Instead, the essence of this question regards how it could be proven that the results arise from the exposure of the individual to the variable. Therefore, it would be equally valid to assess how the EMG principles are applied to ensure that it is applied consistently across groups and that the EMG activity results do not arise from a variable placement of electrodes. Bias could be introduced if there was no standardised electrode placement as it would not be possible to identify if the results relate to if an individual is a case or a control, or if the EMG was applied in the incorrect place.
7	Slight change in the question wording	This question asked if the answer to Q6 was the same for both cases and controls. As Q6 has been modified, the title of this question has been slightly modified to reflect this change.
8		The original question assessed if reporting bias has been introduced through different numbers of participants in each group not responding to follow-up/the variable of interest. This question is not appropriate for the cross-sectional basis of this cohort as there is no follow-up period and the outcome of interest is EMG which, as a passive measurement technique, all participants will respond to. The new structure instead assesses if the task, which is the element of the study which occurs across time, has been implemented in the same way for all participants. This question now therefore assesses if bias may have been introduced through non-standardised task instructions.

Appendix 7 – Specific Outcomes from Each Comparison

Detailed summary of the results presented for each task for each included study within the review.

Study	Task Category	Direction/ Force	Portion	Parameter			Muscle	Result
				Outcome	Interpretation	Normalisation		
Adams, 2006	Trunk Hyperextension	Sagittal	Neutral to extension	iEMG	Absolute	-	Combined Paraspinal	No difference
			Extension to neutral					No difference
	Trunk Axial Rotation	Left	Neutral to rotated					No difference
			Rotated to neutral					No difference
	Trunk Axial Rotation	Right	Neutral to rotated					No difference
			Rotated to neutral					LBP Greater Activity
	Flexion-Extension	Sagittal	Neutral to flexion					LBP Greater Activity
			Flexion to Neutral					No difference
Ambroz et al., 2000	Flexion-Extension	Sagittal	Full Flexion	Amplitude	Absolute	-	Combined Paraspinals	LBP Greater Activity
			Task Mean					LBP Greater Activity
Cimbiz et al., 2006	Trunk Lateral Flexion	Left	Duration	Amplitude	Absolute	-	Combined ES	No difference
	Trunk Lateral Flexion	Right						No difference
	Trunk Flexion	Sagittal						No difference
	Trunk Hyperextension	Sagittal						No difference

	Trunk Rotation (R)	Left						No difference
	Trunk Rotation (L)	Right						No difference
	Prone Trunk extension	Bodyweight						No difference
	Prone Trunk extension	Bodyweight						No difference
	Prone Trunk Extension	Bodyweight						No difference
Cohen et al., 1986	Static 45° trunk flexion	Sagittal Bodyweight	Static	iEMG	Absolute	-	Left paraspinal	No difference
							Right paraspinal	No difference
	Static Trunk flexion	Sagittal Bodyweight					Left paraspinal	No difference
							Right paraspinal	No difference
	Forward Pelvic Tilt	Sagittal					Left paraspinal	No difference
							Right paraspinal	No difference
Collins et al., 1982	Static 45° trunk flexion	Sagittal Bodyweight	Duration/sec	iEMG	Absolute	-	Left paraspinal	No difference
							Right paraspinal	LBP lower activity
	Static Trunk flexion	Sagittal Bodyweight					Left paraspinal	No difference
							Right paraspinal	No difference
	Forward Pelvic Tilt	Sagittal					Left paraspinal	No difference
							Right paraspinal	LBP lower activity

Danneels et al., 2002	Dynamic Stabilisation	Sagittal, Left and Right	Mean for all tasks and reps	Amplitude	Normalised	MVC	Combined Multifidus	No difference
							Combined ES	No difference
de Aquino Nava et al., 2017	Flexion-Extension	Sagittal	Mean for reps	Activation	Normalised	MVC	Combined Multifidus	No difference
							Combined ES	No difference
	Weighted Flexion-Extension	Sagittal, 5% Max					Combined Multifidus	No difference
							Combined ES	No difference
	Weighted Flexion-Extension	Sagittal, 10% Max					Combined Multifidus	No difference
							Combined ES	No difference
Descarreaux et al., 2007	Resisted Trunk Flexion and Extension	50% and 70% MVC	Onset to peak force	iEMG	Normalised	Baseline	Combined Multifidus	No difference
							Combined ES	No difference
Djordjevic et al., 2015	Prone Trunk Extension	Bodyweight	Maximum Value	Amplitude	Normalised	MVC	Combined Multifidus	LBP greater activity
Du et al., 2018	Flexion-Extension	Sagittal	Mean for reps	Amplitude	Normalised	Maximum	Left Multifidus	No difference
				Amplitude			Right Multifidus	No difference
				RMS			Left Multifidus	No difference
				RMS			Right Multifidus	No difference
	Extension-Flexion	Sagittal		Amplitude			Left Multifidus	No difference
				Amplitude			Right Multifidus	No difference
				RMS			Left Multifidus	No difference
				RMS			Right Multifidus	No difference

	Trunk Lateral Flexion	Left		Amplitude			Left Multifidus	No difference
				Amplitude			Right Multifidus	No difference
				RMS			Left Multifidus	No difference
				RMS			Right Multifidus	No difference
	Trunk Lateral Flexion	Right		Amplitude			Left Multifidus	No difference
				Amplitude			Right Multifidus	No difference
				RMS			Left Multifidus	No difference
				RMS			Right Multifidus	No difference
Ershad et al., 2009	Trunk Flexion	Sagittal Bodyweight	Mean	RMS	Normalised	MVC	Right ES	No difference
							Right Multifidus	No difference
	Trunk Flexion	Sagittal BW+6kg		RMS			Right ES	No difference
							Right Multifidus	No difference
	Trunk Flexion	Sagittal BW+12kg		RMS			Right ES	No difference
							Right Multifidus	No difference
Falla et al., 2014	Repeated Box Lifting	Sagittal	Cycles 2-4 - Lifting	RMS	Normalised	Initial Value	Ipsilateral ES	No difference
			Cycles 2-4 - Lowering					No difference
			Cycles 12-14 - Lifting					No difference
			Cycles 12-14 - Lowering					No difference

			Cycles 22-24 - Lifting					LBP Greater Activity
			Cycles 22-24 - Lowering					LBP Greater Activity
Kankaanpaa et al., 2005	Seated Trunk extensions	Sagittal resisted	Initial 5s	Amplitude	Absolute	-	Left Paraspinal	No difference
							Right Paraspinal	No difference
Kankaanpaa et al., 1998	Seated lumbar extension	50% MVC	Initial 5s	Amplitude	Normalised	MVC	Left L3-L4 Paraspinal	No difference
							Right L3-L4 Paraspinal	No difference
							Left L5-S1 Paraspinal	No difference
							Right L5-S1 Paraspinal	No difference
Kienbacher et al., 2017	Seated Flexion-Extension	Sagittal	Combined Movement	RMS	Normalised	80% MVC	Combined Multifidus (18-40)	No difference
							Combined Multifidus (40-60)	LBP Greater Activity
Lariviere et al., 2002	Sagittal box lifting	Sagittal	Lifting	Amplitude	Absolute	-	Left ES	No difference
			Lowering				Left ES	LBP lower activity
			Lifting				Right ES	No difference
			Lowering				Right ES	No difference
	Box lifting with axial rotation	Sagittal and Right	Lifting				Left ES	No difference
			Lowering				Left ES	No difference
			Lifting				Right ES	No difference

			Lowering				Right ES	No difference
Lima at al., 2018	Object lifting	Sagittal	Picking up Object	Mean Difference (RMS)	Absolute	-	Left ES (LN)	LBP Greater Activity
							Left ES (IL)	LBP Greater Activity
							Left Multifidus	No difference
							Right ES (LN)	LBP Greater Activity
							Right ES (IL)	LBP Greater Activity
							Right Multifidus	LBP Greater Activity
			Placing Object down				Left ES (LN)	LBP Greater Activity
							Left ES (IL)	LBP Greater Activity
							Left Multifidus	LBP Greater Activity
							Right ES (LN)	LBP Greater Activity
							Right ES (IL)	LBP Greater Activity
							Right Multifidus	LBP Greater Activity
Lin et al., 2001	Maximal Flexion	Sagittal	Change from neutral	Mean Change (iEMG)	Normalised	MVC	Combined ES	LBP Greater Change
	Maximal Extension	Sagittal					Combined ES	LBP Lower Change
		Left	Initial 5% of Task	RMS	Normalised	MVC	Left ES (IL)	No difference

Ng et al., 2002a	Resisted Trunk rotation						Left Multifidus	No difference
							Right ES (IL)	No difference
							Right Multifidus	No difference
							Left ES (IL)	No difference
	Resisted Trunk rotation	Right					Left Multifidus	LBP Greater Activity
							Right ES (IL)	No difference
							Right Multifidus	No difference
Ng et al., 2002b	Resisted Trunk rotation	Left	All reps and levels	RMS	Normalised	MVC	Left ES (IL)	No difference
							Left Multifidus	LBP Lower Activity
							Right ES (IL)	No difference
							Right Multifidus	No difference
	Resisted Trunk rotation	Right					Left ES (IL)	No difference
							Left Multifidus	No difference
							Right ES (IL)	No difference
							Right Multifidus	No difference
Pirouzi et al., 2006	Resisted Axial Rotation	Left, 25% MVC	Position 1 at Maximal	RMS	Normalised	SMVC	Left ES	No difference
							Right ES	No difference
	Resisted Axial Rotation		Position 2 at Maximal				Left ES	No difference
							Right ES	No difference
	Resisted Axial Rotation		Position 3 at Maximal				Left ES	No difference
							Right ES	No difference

	Resisted Axial Rotation	Right, 25% MVC	Position 4 at Maximal				Left ES	LBP Greater Activity
							Right ES	LBP Greater Activity
	Resisted Axial Rotation		Position 1 at Maximal				Left ES	No difference
							Right ES	No difference
	Resisted Axial Rotation		Position 2 at Maximal				Left ES	No difference
							Right ES	No difference
	Resisted Axial Rotation		Position 3 at Maximal				Left ES	No difference
							Right ES	No difference
	Resisted Axial Rotation		Position 4 at Maximal				Left ES	No difference
							Left ES	No difference
Rossi et al., 2017	Resisted Seated Flexion	Maximal	All reps combined	RMS	Absolute	-	Left ES (LN)	LBP Lower Activity
							Left Multifidus	LBP Lower Activity
							Right ES (LN)	LBP Lower Activity
							Right Multifidus	No difference
	Resisted Seated Extension	Maximal					Left ES (LN)	LBP Lower Activity
							Left Multifidus	No difference
							Right ES (LN)	LBP Lower Activity
							Right Multifidus	No difference
Shirado et al., 1995	Flexion-Extension	Sagittal	Neutral to Flexion	RMS	Normalised	Initial Value	Combined ES	LBP Greater Activity

			Maximal Flexion				Combined ES	LBP Continued Activity
			Flexion to Neutral				Combined ES	LBP Lower Activity
Yang, 2018	Flexion	Sagittal	3s averaged	RMS	Normalised	RVC	Right Multifidus	LBP Lower Activity
	Weighted Flexion	Sagittal + 10% BW					Right Multifidus	LBP Lower Activity
	Weighted Flexion	Sagittal + 20% BW					Right Multifidus	LBP Lower Activity
	All Tasks	Sagittal	All tasks averaged				Right Multifidus	LBP Lower Activity

Appendix 8 – Ethical Review, Consent Forms and Patient Information Sheets for Chapter Three

UNIVERSITY OF BIRMINGHAM
APPLICATION FOR ETHICAL REVIEW

Who should use this form:

This form is to be completed by PIs or supervisors (for PGR student research) who have completed the University of Birmingham's Ethical Review of Research Self Assessment Form (SAF) and have decided that further ethical review and approval is required before the commencement of a given Research Project.

Please be aware that all new research projects undertaken by postgraduate research (PGR) students first registered as from 1st September 2008 will be subject to the University's Ethical Review Process. PGR students first registered before 1st September 2008 should refer to their Department/School/College for further advice.

Researchers in the following categories are to use this form:

1. The project is to be conducted by:
   - staff of the University of Birmingham; or
   - postgraduate research (PGR) students enrolled at the University of Birmingham (to be completed by the student's supervisor);
2. The project is to be conducted at the University of Birmingham by visiting researchers.

Students undertaking undergraduate projects and taught postgraduate (PGT) students should refer to their Department/School for advice.

NOTES:

- An electronic version of the completed form should be submitted to the Research Ethics Officer, at the following email address: aer-ethics@contacts.bham.ac.uk. Please **do not** submit paper copies.
- If, in any section, you find that you have insufficient space, or you wish to supply additional material not specifically requested by the form, please it in a separate file, clearly marked and attached to the submission email.
- If you have any queries about the form, please address them to the Research Ethics Team.

☒ **Before submitting, please tick this box to confirm that you have consulted and understood the following information and guidance and that you have taken it into account when completing your application:**

- **The information and guidance provided on the University's ethics webpages (https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research-Ethics/Ethical-Review-of-Research.aspx)**
- **The University's Code of Practice for Research (http://www.as.bham.ac.uk/legislation/docs/COP_Research.pdf)**

UNIVERSITY OF BIRMINGHAM APPLICATION FOR ETHICAL REVIEW	*OFFICE USE ONLY:* Application No: Date Received:

1. TITLE OF PROJECT

Investigating the variability of muscular activity distribution and muscular stiffness in NSLBP patients, when compare it with healthy controls

2. THIS PROJECT IS:

University of Birmingham Staff Research project ☐
University of Birmingham Postgraduate Research (PGR) Student project ☒
Other ☐ (Please specify):

3. INVESTIGATORS

a) PLEASE GIVE DETAILS OF THE PRINCIPAL INVESTIGATORS OR SUPERVISORS (FOR PGR STUDENT PROJECTS)

Name: Title / first name / family name	Dr. Nicola Heneghan
Highest qualification & position held:	Lecturer
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

Name: Title / first name / family name	Professor Deborah Falla
Highest qualification & position held:	Chair in Rehabilitation Science and Physiotherapy
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

Name: Title / first name / family name	Dr. Alison Rushton
Highest qualification & position held:	Senior Lecturer
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

b) PLEASE GIVE DETAILS OF ANY CO-INVESTIGATORS OR CO-SUPERVISORS (FOR PGR STUDENT PROJECTS)

Name: Title / first name / family name	
Highest qualification & position held:	
School/Department	
Telephone:	
Email address:	

c) In the case of PGR student projects, please give details of the student

Name of student:	Carlos Murillo	Student No:
Course of study:	MRes Exercise and Sport	Email
Principal	Dr. Nicola Heneghan	

4. ESTIMATED START OF PROJECT Date: 1/8/2017

ESTIMATED END OF PROJECT Date: 1/11/2017

5. FUNDING

List the funding sources (including internal sources) and give the status of each source.

Funding Body	*Approved/Pending /To be submitted*

If you are requesting a quick turnaround on your application, please explain the reasons below (including funding-related deadlines). You should be aware that whilst effort will be made in cases of genuine urgency, it will not always be possible for the Ethics Committees to meet such requests.

6. SUMMARY OF PROJECT

Describe the purpose, background rationale for the proposed project, as well as the hypotheses/research questions to be examined and expected outcomes. This description should be in everyday language that is free from jargon. Please explain any technical terms or discipline-specific phrases.

Low Back Pain (LBP) is one of the most common musculoskeletal disorders in the world (Hoy *et al.,* 2012) and particularly, chronic nonspecific low back pain (CNSLBP) representing around 23% of LBP cases (Krismer and Van Tulder, 2007). The total cost of its management is a great economic burden, up to $US90 billion in the United States (Dagenais *et al*., 2008).

Whilst there are some identified risk factors, including age, body mass and composition, psychological factors or fatiguing tasks (Macfarlane *et al.,* 1997; Hoogendoorn *et al.,* 2000; Hoy *et al.,* 2010) little is known about the involvement of lumbar spinal muscles in LBP including muscle stiffness. A novel technique, shear wave elastography (SWE), allows the non-invasive quantification of muscular stiffness by using shear elastic modulus (Nordez and Hug, 2010; Brandenburg *et al.,* 2014; Ryu and Jeong, 2017). Furthermore, shear elastic modulus can be used for assessing the active muscular stiffness and the changes in load sharing during fatiguing tasks (Bouillard *et al.,* 2012). This technique is therefore suitable for use in the lumbar spine (Moreau *et al.,* 2016).

One area that has been researched is the strength of back muscles, where controversial findings have been described about the relationship between insufficient isometric strength and LBP using the Sørensen test (Demoulin et al., 2006). However, the Ito test (Ito et al., 1996) has shown to more specifically assess the lumbar muscles endurance and it might clarify this question (Muller et al, 2010). Another dysfunction strongly linked with LBP is the absence or reduction of the Flexion Relaxation Phenomenon (FRP) (Geisser *et al.,* 2005). FRP was described by Floyd and Silver (1955) and refers to the reduction of paraspinal muscle activity during a full forward bend. The FRP is measured by the flexion relaxation ratio (Watson *et al.,* 1997) and has been used as indicator of recovery of LBP (Mayer *et al.,* 2009). It is hypothesised that in pain-free participants, although paraspinal muscular activity decreases, muscles would still provide tension to avoid excessive load on the passive structures of the lumbar spine (McGill and Kippers, 1994). Traditionally, the FRP and the lumbar endurance tests have been measured using bipolar EMG (Schinkel-Ivy *et al*., 2013; Coorevits *et al.,* 2008). However, recent studies have used high-density electromyography (HDEMG) in endurance tests such as sustained trunk flexion, repetitive flexion and the modified Sørensen test (Tucker *et al.,* 2009; Falla *et al.,* 2014; Abboud *et al.,* 2014; Abboud, Nougarou and Descarreaux, 2016). This recent electromyography method has revealed differences in distribution of muscular activity between LBP patients and pain-free participants (Abboud *et al.,* 2014; Falla *et al.,* 2014). In addition, a higher distribution has been associated with a delay in the fatigue (Abboud *et al.,* 2014; Farina *et al.,* 2008).

Consequently, changes in the muscular activation of the back muscles might result in an altered muscular stiffness to change the load in the painful area but it might reduce negatively the active stability of the spine (Lieber and Ward, 2013; Panjabi, 2003). On the basis of the above, we consider that knowing the implication of muscular stiffness in LBP as well as its relationship with muscular activation is relevant to improve the current rehabilitation interventions in LBP population.

Given the current evidence for muscular involvement in LBP, and the identified gaps the aim of this study is:

- To compare the differences in muscular activity distribution and variability of shear elastic modulus by using SWE and HDEMG between healthy and NSLBP participants.

Secondary objectives:

- To investigate muscular stiffness during isometric contraction of the lumbar muscles and compare NSLBP and healthy participants
- To compare differences in in the distribution of muscular activation during the FRP test between LBP and healthy participants.
- To compare the relationship between activity distribution and holding time during an endurance task of the lumbar extensor muscles (the Ito test).

7. CONDUCT OF PROJECT

Please give a description of the research methodology that will be used

Design: Case control observational study.

All studies will be conducted in the CPR Spine laboratory of the School of Sport, Exercise and Rehabilitation Sciences.

Equipment:

- SWE LOGIQ S8 (GE Healthcare, Chicago USA) (CE MARKED) in "Elasto" shear wave setting be used with the 9L probe in 'small parts mode'.
- Surface EMG signals will be detected with a semi-disposable adhesive grid of 13 rows and 5 columns electrodes (SPES Medica, Salerno, Italy) and bipolar electrodes. The EMG signals will be amplified (EMG-USB 2, 400-channel EMG amplifier, OT 8 Bioelettronica, Torino, Italy, 3dB, bandwidth 10-500 Hz)

The study will be divided in 4 stages: pre-muscle stiffness (passive and active) assessment, flexion relaxation phenomena, endurance test and post muscle stiffness assessment. Previous to the experiment, the participants will complete the following questionnaires:

- Oswestry Disability Index (ODI) for disability (Fairbank and Pynsent, 2000).
- Short Form (SF)-36 Health Survey forgeneral health status of the participant (Brazier *et al.,* 1992)
- Tampa Scale for Kinesiophobia (TSK) for fear-avoidance behavior and fear-avoidance beliefs (Vlaeyen *et al.,* 1995)
- Pain Numeric Rating Scale (NRS) for pain

Pre and post muscle stiffness assessment with Shear Wave Elastography:

- For the assessment of passive stiffness, participants will lie in prone with a pillow placed under the lower abdomen and pelvis.
- For the assessment of active stiffness, the head of the examination table will be lowed and participants will be requested to hold the position for 10-15 seconds.
- Measurements will be taken bilaterally in the middle of the electrode area with a transversal orientation.
- A mark will be drawn on the skin, parallel to the muscle fibres and in the middle of the electrode area, for positioning the ultrasound probe.
- Deep and superficial layers of the multifidus will be measured.
- The probe applied with minimal compression to the skin.
- The Region of Interest (ROI) will be established on the first acquisition with the mean shear modulus calculated.
- A mean of 3 shear modulus measurements will be taken.

EMG:

- The subject's skin will be prepared by gentle local abrasion using abrasive paste (Medic-Every, Parma, Italy) and cleaned with water.
- Electrode grids will be positioned 2 cm lateral to the lumbar spinous process midpoint, covering the low back from the level of L5 to approximately L2. The electrode grids will be placed bilaterally.
- Thirty microliters of conductive paste will be inserted into each cavity of the grid to provide electrode-skin contact.
- Bipolar electrodes will be placed over the external oblique and rectus abdominis muscles bilaterally
- The reference electrode will be place at C7 level

Flexion relaxation phenomena

The participants will perform 3 FRP in standing with 30 seconds rest between each repetition (Solomonow et al., 2003; Schinkel-Ivy et al, 2013). The performance of the test will be: bending forward for 4 seconds, maintaining the full flexion for 8 seconds and returning to the standing position in 4 seconds. The timing of the protocol will be assisted by a metronome with 60 BPM. An inertial sensor will be placed over the participants spine to track the range of spinal movement.

Endurance task - Ito test
A similar protocol applied by Ito et al (1996) will be used in the study. The participant will lie on the examination table with a pillow under the pelvis and without fixation. Then, the participants will be requested to lift the upper trunk with a simultaneous contraction of the buttocks to stabilize the pelvis and with the cervical spine in full flexion. The participant will hold the arms parallel to the body axis without any contact to the pillow. The participant will have to hold the position up to the point of task failure. Task failure will be defined as deviation of 10 degrees of the initial position measure by electronic goniometer or exacerbation of the symptoms. The evolution of the symptoms during the test will be quantify by the NRS
The resting time between FRP protocol and Ito test will be 5 minutes

8. DOES THE PROJECT INVOLVE PARTICIPATION OF PEOPLE OTHER THAN THE RESEARCHERS AND SUPERVISORS?

Yes ☒ No ☐

Note: 'Participation' includes both active participation (such as when participants take part in an interview) and cases where participants take part in the study without their knowledge and consent at the time (for example, in crowd behaviour research).

If you have answered NO please go to Section 18. If you have answered YES to this question please complete all the following sections.

9. PARTICIPANTS AS THE SUBJECTS OF THE RESEARCH
Describe the number of participants and important characteristics (such as age, gender, location,

affiliation, level of fitness, intellectual ability etc.). Specify any inclusion/exclusion criteria to be used.

A sample of 20 healthy participants and 20 participants who experience chronic non-specific LBP (NSLBP) will be recruited similar to previous case control studies (Falla et al., 2014)

- Both females and males are eligible for the study.
- The age range will be restricted to 20-50 years old. Differences in muscular activation in trunk flexion have been described between >60 years old participants and younger groups. (Kienbacher et al., 2015)
- LBP and control participants will have the capacity to give the consent at his/her own will.

Control group:
Inclusion criteria:

- Pain-free participants will be included if they have no relevant history of back or lower limb pain or injury that limited their function and/or required treatment from a health profession.
- Independently mobile

Exclusion

- Neurologic problems: stroke
- Chronic Respiratory problems: Bronchiectasis or COPD
- Cardiovascular diseases: high blood pressure, angina, heart attack

LBP group:
Inclusion criteria:

- Individuals with chronic NSLBP with a sufficient intensity to limit the function will be considered for the study (Falla et al., 2014)
- The definition for NSLBP is low back pain which is not related to serious pathology and/or does not have a specific cause. Chronic refers to at least 3 months of episode duration and pain at least half the days in the past 6 months (Von Korff, 1994).
- Independently mobile

Exclusion criteria:

- Concurrent systemic, rheumatic or neuro-musculoskeletal disorders which may confound testing or are currently pregnant.
- Radicular low back pain or pain related to trauma, fractures, spinal stenosis.
- Participants with severe pain (>7 in Numerical Rating Scale (NRS)) the day of the data collection will also be excluded for ethical reasons, due to the endurance protocol may be able to exacerbate their symptoms
- Participants under active management of LBP in the National Health Service (NHS) through specific medications prescribed by a GP, consultant or therapists (physiotherapist, osteopath, chiropractor) less than 3 months before the possible enrolment.

10. RECRUITMENT

Please state clearly how the participants will be identified, approached and recruited. Include any relationship between the investigator(s) and participant(s) (e.g. instructor-student).

Note: Attach a copy of any poster(s), advertisement(s) or letter(s) to be used for recruitment.

All participants will be recruited via poster advertisement and social media, from the community and population of staff and students at the University of Birmingham.
Interested participants will be asked to contact the PI through email.
All information regarding the experiment will be provided in the 'Participant Information Leaflet', that will be provided to interested participants.
The investigators involved in this project will explain the experiment procedures to the participants and answer any questions they may have.
The investigators' telephone numbers and e-mail addresses will be provided on the 'Informed Consent' and 'Participant Information Leaflet'.
Data collection will take place in the School of Sport, Exercise and Rehabilitation Sciences, at the CPR spine laboratory from 1st August.

11. CONSENT

a) Describe the process that the investigator(s) will be using to obtain valid consent. If consent is not to be obtained explain why**.** If the participants are minors or for other reasons are not competent to consent, describe the proposed alternate source of consent, including any permission / information letter to be provided to the person(s) providing the consent.

Written informed Consent (see attached) will be obtained after the study has been explained and the volunteers have the opportunity to ask any questions they may have before the data collection.

Note: Attach a copy of the Participant Information Sheet (if applicable), the Consent Form (if applicable), the content of any telephone script (if applicable) and any other material that will be used in the consent process.

b) Will the participants be deceived in any way about the purpose of the study? **Yes** ☐ **No** ☒

If yes, please describe the nature and extent of the deception involved. Include how and when the deception will be revealed, and who will administer this feedback.

12. PARTICIPANT FEEDBACK

Explain what feedback/ information will be provided to the participants after participation in the research. (For example, a more complete description of the purpose of the research, or access to the results of the research).

Participants will be invited to leave their email address to receive the publication of the study results.

13. PARTICIPANT WITHDRAWAL

a) Describe how the participants will be informed of their right to withdraw from the project.

The participants' right to withdraw from taking or continuing the experiment will be clearly reported on the Consent Form and PIF and will also be expressed verbally to the participants. Participants will be free to withdraw at any time during the experimental session and will have the right to withdraw their data from the study up to 2 weeks the following data collection without giving a reason. They will need to contact with the PI by email.

b) Explain any consequences for the participant of withdrawing from the study and indicate what will be done with the participant's data if they withdraw.

There are no consequences for withdrawing from the study. In case of experiment interruption or withdrawal by the participant, personal data for participant identification and all the data acquired until the point of withdrawal will be deleted.

14. COMPENSATION

Will participants receive compensation for participation?

i) Financial **Yes** ☒ **No** ☐

ii) Non-financial **Yes** ☐ **No** ☐

If **Yes** to **either** i) or ii) above, please provide details.

Participant will be reimbursed for travelling to the university. Funds will come from MRes student bench fees.

If participants choose to withdraw, how will you deal with compensation?

The participants who withdraw following data collection will still eligible for the reimbursement for the sessions that they attended.

15. CONFIDENTIALITY

a) Will all participants be anonymous? **Yes** ☒ **No** ☐

b) Will all data be treated as confidential? **Yes** ☒ **No** ☐

Note: Participants' identity/data will be confidential if an assigned ID code or number is used, but it will not be anonymous. Anonymous data cannot be traced back to an individual participant.

Describe the procedures to be used to ensure anonymity of participants and/or confidentiality of data both during the conduct of the research and in the release of its findings.

Participants will not be anonymus to the research team, however, all participant information and data will be stored anonymously with their ID number. Only necessary personal data will be collected during the study. All of the data will be kept securely and will remain strictly confidential throughout. The data will only be shared with the participant, investigator and research team. All data will be kept for 10 years in line with the University of Birmingham Research Governance Guidelines. Personal and experimental data for participants who withdraw will be deleted up to the withdrawal deadline.

If participant anonymity or confidentiality is not appropriate to this research project, explain, providing details of how all participants will be advised of the fact that data will not be anonymous or confidential.

Not applicable

16. STORAGE, ACCESS AND DISPOSAL OF DATA

Describe what research data will be stored, where, for what period of time, the measures that will be put in place to ensure security of the data, who will have access to the data, and the method and timing of disposal of the data.

All data will be stored securely in electronic format in a mass spreadsheet on a secure University server with access limited to the research team only,CM, NH, DF and AR. Access to the data will require a password, and all data will be stored anonymously to ensure full protection and privacy of participants. The investigators and study supervisor will have access to the data. Consent forms and questionnaires will be securely stored in a lock cabine and kept for 10 years under the University of Birmingham Research Guidelines. Digital data will be stored in an university laptop with secure code.

17. OTHER APPROVALS REQUIRED? e.g. Criminal Records Bureau (CRB) checks or NHS R&D approvals.

☐ YES ☒ NO ☐ NOT APPLICABLE

If yes, please specify.

18. SIGNIFICANCE/BENEFITS

Outline the potential significance and/or benefits of the research

There is no immediate benefit to the participants of the study. However the results of this project will increase our understanding of changes in muscular activity and muscular stiffness to LBP. This knowledge is relevant for the development and design of rehabilitation programs for individuals with LBP.

19. RISKS

a) Outline any potential risks to **INDIVIDUALS**, including research staff, research participants, other individuals not involved in the research and the measures that will be taken to minimise any risks and the procedures to be adopted in the event of mishap

There are not adverse effects for any of the procedures within the study and any hazards have been minimalized as detailed in the risk assessment attached. The examiner will be an experienced physiotherapist and will be paying special attention to monitoring any changes in symptoms during the protocol. If the participants experience any discomfort or exacerbation in their current symptoms during the endurance test, it will be ceased.

b) Outline any potential risks to **THE ENVIRONMENT and/or SOCIETY** and the measures that will be taken to minimise any risks and the procedures to be adopted in the event of mishap.

No risks to the environment and/or society can be identified in this study.

20. ARE THERE ANY OTHER ETHICAL ISSUES RAISED BY THE RESEARCH?

Yes ☐ **No** ☒

If yes, please specify

21. EXPERT REVIEWER/OPINION

You may be asked to nominate an expert reviewer for certain types of project, including those of an interventional nature or those involving significant risks. If you anticipate that this may apply to your work and you would like to nominate an expert reviewer at this stage, please provide details below.

Contact details (including email address)
Brief explanation of reasons for nominating and/or nominee's suitability

22. CHECKLIST

Please mark if the study involves any of the following:

- Vulnerable groups, such as children and young people aged under 18 years, those with learning disability, or cognitive impairments ☐
- Research that induces or results in or causes anxiety, stress, **pain** or physical discomfort, or poses a risk of harm to participants (which is more than is expected from everyday life) ☒
- Risk to the personal safety of the researcher ☐
- Deception or research that is conducted without full and informed consent of the participants at time study is carried out ☐
- Administration of a chemical agent or vaccines or other substances (including vitamins or food substances) to human participants. ☐
- Production and/or use of genetically modified plants or microbes ☐
- Results that may have an adverse impact on the environment or food safety ☐
- Results that may be used to develop chemical or biological weapons ☐

Please check that the following documents are attached to your application.

	ATTACHED	NOT APPLICABLE
Recruitment advertisement	☒	☐
Participant information sheet	☒	☐
Consent form	☒	☐
Questionnaire	☒	☐
Interview Schedule	☐	☒

23. DECLARATION BY APPLICANTS

I submit this application on the basis that the information it contains is confidential and will be used by the University of Birmingham for the purposes of ethical review and monitoring of the research project described herein, and to satisfy reporting requirements to regulatory bodies. The information will not be used for any other purpose without my prior consent.

I declare that:

- The information in this form together with any accompanying information is complete and correct to the best of my knowledge and belief and I take full responsibility for it.
- I undertake to abide by University Code of Practice for Research (http://www.as.bham.ac.uk/legislation/docs/COP_Research.pdf) alongside any other relevant professional bodies' codes of conduct and/or ethical guidelines.
- I will report any changes affecting the ethical aspects of the project to the University of Birmingham Research Ethics Officer.
- I will report any adverse or unforeseen events which occur to the relevant Ethics Committee via the University of Birmingham Research Ethics Officer.

Name of principal investigator/project supervisor:	
Date:	

Please now save your completed form, print a copy for your records, and then email a copy to the Research Ethics Officer, at aer-ethics@contacts.bham.ac.uk. As noted above, please do not submit a paper copy.

The University of Birmingham

School of Sport, Exercise and Rehabilitation Sciences

Participant Information Form

Study title: Investigating the variability of muscular activity distribution and muscular stiffness in NSLBP patients, when compared with healthy controls

Investigators: Mr Carlos Murillo, Prof Deborah Falla, Dr Alison Rushton and Dr Nicola Heneghan

1. Invitation

You are being invited to take part in a research study. Before you decide to participate it is important you understand why the research is being done and what it will involve. Please take time to read the following information sheet carefully and discuss it with the researcher or others if you wish.

2. What is the purpose of the study?

Low Back Pain (LBP) is one of the most common musculoskeletal disorders in the world and particularly, Chronic Nonspecific Low Back Pain (CNSLBP) represents around 23% of LBP cases. Age, BMI, psychological factors and weakness of back muscles have all been described as risk factors for LBP. The impact of muscle properties on their function is somewhat unknown, for example there is no conclusive evidence associating muscle stiffness with the recurrence of LBP. State-of-the-art devices such as Shear wave Elastography and High-Density Electromyography will allow us to investigate the effect of muscular stiffness in LBP as well as its relationship with muscular activation. It may inform future research to improve the current rehabilitation interventions in LBP population

3. Why have I been chosen?

You have been chosen because we understand you do not have previous relevant history of Low Back pain.

You cannot take part in this study if you are over 50 or under 20 years old or if you suffer from concurrent systemic issues such as rheumatic or neuro-musculoskeletal disorders. Also, you cannot if you have (current or past) neurologic problems (such as stroke), chronic respiratory problems (such as bronchiectasis or COPD) or cardiovascular conditions (such as high blood pressure, angina or heart attack). In addition, you cannot take part in this study if you are pregnant.

4. Do I have to take part?

You are free to decide whether you participate or not. You will be given an information sheet to keep, and you will be asked to complete a brief screening questionnaire and answer some questions. Should you meet the inclusion criteria, you will be invited to sign a consent form before taking part in the study. If you do agree to take part you are free to withdraw at any time up to 2 weeks following the data collection without giving a reason by communicating to any member of the research team by email.
If you withdraw from the study, your personal data and all the data acquired until the point of withdrawal will be deleted and destroyed.
Furthermore, the researchers will provide further information about the purpose of this study if you want and you will be invited to leave their email address to receive the publication of the study results.
You will be reimbursed for travelling to the university

5. Are risks involved in participation?

All of the possible risks have been assessed and procedures put in place to minimize any risk to participants. However, the researchers who are qualified physiotherapists will monitor your responses to testing. If you experience any significant discomfort or pain testing will stopped

The risks of the first part of the test (bend forward) are similar to those experienced during every day activities e.g. picking up an object. In the case of the endurance test, testing will be stopped ceased if any significant discomfort is experienced.

6. What do I have to do?

You will be asked to visit the CPR Spine laboratory in the School of Sport, Exercise and Rehabilitation Sciences. You will be asked to do the following

- Complete a questionnaire about your pain intensity and its involvement in your daily activities.
- You will be asked to lie face down on the plinth. We will take the measurements of muscle stiffness from your lower back region by using an ultrasound. Then, you will be requested to actively maintain an unsupported horizontal position for 15 seconds while the same measurement is taken. If any discomfort is provoked during the test, the test will be ceased.
- Stand up and do 3 bends forward in sets of 12 seconds.
- Do an endurance test of lumbar muscles while muscular activity is assessed by using electromyography. The endurance test will involve performing a gentle extension of the trunk up to fatigue facing down. Electromyography is a technique for recording the electrical activity produced by your muscles by placing electrodes on your skin. There are no discernible risks and you would not feel anything other than the adhesion of the electrodes to your skin.
- Repeat the measurements of muscular stiffness lying on the plinth.
- The visit will last 2 hours
- You will be free to stop the test at any time during the visit for any reason including if you experience significant discomfort beyond that which would be associated with normal muscle contraction

7. Will my taking part in this study be kept confidential?

All information collected on you will be kept strictly confidential. Personal information will be retained, but only available to the researchers using password protected files. All data for presentation will be anonymised and aggregated, so your identity will not be revealed in any way.

8. What will happen to the results of the research study?

The findings from this study will be shared with other researchers in the form of presentations and scientific papers as appropriate. These will be used to help inform the development of new approaches for managing individuals with CNSLBP.

9. Who is organising and funding the research?

The study has been designed and organised by Mr Carlos Murillo, Dr Nicola Heneghan, Prof Deborah Falla and Dr Alison Rushton and supported by research assistants from the Centre of Precision Rehabilitation for Spinal Pain. No funding has been given towards this study.

10. Contact for further information

Investigators:
Mr Carlos Murillo, co-investigator,
Dr Nicola Heneghan, Principle investigator,
Prof Deborah Falla
Dr Alison Rushton

Thank you for taking time to read this and considering taking part in the study.

The University of Birmingham

School of Sport, Exercise and Rehabilitation Sciences

Participant Information Form

Study title: Investigating the variability of muscular activity distribution and muscular stiffness in NSLBP patients, when compared with healthy controls

Investigators: Mr Carlos Murillo, Prof Deborah Falla, Dr Alison Rushton and Dr Nicola Heneghan

10. Invitation

You are being invited to take part in a research study. Before you decide to participate it is important you understand why the research is being done and what it will involve. Please take time to read the following information sheet carefully and discuss it with the researcher or others if you wish.

11. What is the purpose of the study?

Low Back Pain (LBP) is one of the most common musculoskeletal disorders in the world and particularly, Chronic Nonspecific Low Back Pain (CNSLBP) represents around 23% of LBP cases. Age, BMI, psychological factors and weakness of back muscles have all been described as risk factors for LBP. The impact of muscle properties on their function is somewhat unknown, for example there is no conclusive evidence associating muscle stiffness with the recurrence of LBP. State-of-the-art devices such as Shear wave Elastography and High-Density Electromyography will allow us to investigate the effect of muscular stiffness in LBP as well as its relationship with muscular activation. It may inform future research to improve the current rehabilitation interventions in LBP population

12. Why have I been chosen?

You have been chosen because we understand you have had Low Back Pain for at least 3 of the last 6 months not related to trauma, fractures or spinal stenosis

You cannot be selected for this study if you are over 50 or under 20 years old, or if you suffer from concurrent systemic issues such as rheumatic or neuro-musculoskeletal disorders. Also, you cannot if you have (current or past) neurologic problems (such as stroke), chronic respiratory problems (such Bronchiectasis or COPD) or cardiovascular conditions (such as high blood pressure, angina or heart attack).

In addition, you cannot take part if you have been diagnosed with spinal fractures, disc herniation or spinal stenosis or if you are currently pregnant.

13. Do I have to take part?

You are free to decide whether you participate or not. You will be given an information sheet to keep, and you will be asked to complete a brief screening questionnaire and answer some questions. Should you meet the inclusion criteria, you will be invited to sign a consent form before taking part in the study. If you do agree to take part you are free to withdraw at any time up to 2 weeks following the data collection without giving a reason by communicating to any member of the research team by email.

If you withdraw from the study, your personal data and all the data acquired until the point of withdrawal will be deleted and destroyed.

Furthermore, the researchers will provide further information about the purpose of this study if you want and you will be invited to leave their email address to receive the publication of the study results.

You will be compensated £15

14. Are risks involved in participation?

All of the possible risks have been assessed and procedures put in place to minimize any risk to participants. However, the researchers who are qualified physiotherapists will monitor your responses to testing. If you experience any significant discomfort or pain testing will stopped

The risks of the first part of the test (bend forward) are similar to those experienced during every day activities e.g. picking up an object. In the case of the endurance test, testing will be stopped ceased if any significant discomfort is experienced.

15. What do I have to do?

You will be asked to visit the CPR Spine laboratory in the School of Sport, Exercise and Rehabilitation Sciences. You will be asked to do the following

- Complete a questionnaire about your pain intensity and its involvement in your daily activities.
- You will be asked to lie face down on the plinth. We will take the measurements of muscle stiffness from your lower back region by using an ultrasound. Then, you will be requested to actively maintain an unsupported horizontal position for 15 seconds while the same measurement is taken. If any symptoms are provoked during the test, the test will be ceased.
- Stand up and do 3 bends forward in sets of 12 seconds.
- Do an endurance test of lumbar muscles while muscular activity is assessed by using electromyography. The endurance test will involve performing a gentle extension of the trunk up to fatigue facing down. Electromyography is a technique for recording the electrical activity produced by your muscles by placing electrodes on your skin. There are no discernible risks and you would not feel anything other than the adhesion of the electrodes to your skin.
- Repeat the measurements of muscular stiffness lying on the plinth.
- The visit will last 2 hours
- You will be free to stop the test at any time during the visit for any reason including if you experience significant discomfort beyond that which would be associated with normal muscle contraction

16. Will my taking part in this study be kept confidential?

All information collected on you will be kept strictly confidential. Personal information will be retained, but only available to the researchers using password protected files. All data for presentation will be anonymised and aggregated, so your identity will not be revealed in any way.

17. What will happen to the results of the research study?

The findings from this study will be shared with other researchers in the form of presentations and scientific papers as appropriate. These will be used to help inform the development of new approaches for managing individuals with CNSLBP.

18. Who is organising and funding the research?

The study has been designed and organised by Mr Carlos Murillo, Dr Nicola Heneghan, Prof Deborah Falla and Dr Alison Rushton and supported by research assistants from the Centre of Precision Rehabilitation for Spinal Pain. No funding has been given towards this study.

10. Contact for further information

Investigators:
Mr Carlos Murillo, co-investigator,
Dr Nicola Heneghan, Principle investigator,
Prof Deborah Falla
Dr Alison Rushton

Thank you for taking time to read this and considering taking part in the study.

CONSENT FORM

Project title: Investigating the variability of muscular activity distribution and muscular stiffness in NSLBP patients, when compare it with healthy controls

Researchers: Mr Carlos Murillo, Prof Deborah Falla, Dr Alison Rushton and Dr Nicola Heneghan

Contact email:

This information is being collected as part of a research project concerned with the investigation of the relationship between muscular stiffness and muscular activity to manage chronic LBP, by the School of Sport, Exercise and Rehabilitation Sciences at the University of Birmingham. The information which you supply and that which may be collected as part of the research project will be entered into a filing system or database and will only be accessed by authorised personnel involved in the project. The information will be retained by the University of Birmingham and will only be used for the purpose of research and statistical and audit purposes. By supplying this information you are consenting to the University storing your information for the purposes stated above. The information will be processed by the University of Birmingham in accordance with the provisions of the Data Protection Act 1998. No identifiable personal data will be published.

I confirm that I have read and understand the participant information leaflet for this study. I have had the opportunity to ask questions if necessary and have had these answered satisfactorily	
I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason as I will have the right to withdraw my data from the study up to 2 weeks after data collection. If I withdraw my data will be removed from the study and will be destroyed. Participants will be free to withdraw at any time during the experimental session.	
I understand that my personal data will be processed for the purposes detailed above, in accordance with the Data Protection Act 1998	
Based upon the above, I agree to take part in this study	

Name of participant……

Date ……. Signature ……..

Appendix 9 – Ethical Review, Ethical Amendments, Consent Forms and Patient Information Sheets for Chapters Four and Five

UNIVERSITY OF BIRMINGHAM
APPLICATION FOR ETHICAL REVIEW

Who should use this form:

This form is to be completed by PIs or supervisors (for PGR student research) who have completed the University of Birmingham's Ethical Review of Research Self Assessment Form (SAF) and have decided that further ethical review and approval is required before the commencement of a given Research Project.

Please be aware that all new research projects undertaken by postgraduate research (PGR) students first registered as from 1st September 2008 will be subject to the University's Ethical Review Process. PGR students first registered before 1st September 2008 should refer to their Department/School/College for further advice.

Researchers in the following categories are to use this form:

1. The project is to be conducted by:
   - staff of the University of Birmingham; or
   - postgraduate research (PGR) students enrolled at the University of Birmingham (to be completed by the student's supervisor);
2. The project is to be conducted at the University of Birmingham by visiting researchers.

Students undertaking undergraduate projects and taught postgraduate (PGT) students should refer to their Department/School for advice.

NOTES:

- An electronic version of the completed form should be submitted to the Research Ethics Officer, at the following email address: aer-ethics@contacts.bham.ac.uk. Please **do not** submit paper copies.
- If, in any section, you find that you have insufficient space, or you wish to supply additional material not specifically requested by the form, please it in a separate file, clearly marked and attached to the submission email.
- If you have any queries about the form, please address them to the Research Ethics Team.

☒ **Before submitting, please tick this box to confirm that you have consulted and understood the following information and guidance and that you have taken it into account when completing your application:**

- **The information and guidance provided on the University's ethics webpages (https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research-Ethics/Ethical-Review-of-Research.aspx)**
- **The University's Code of Practice for Research (http://www.as.bham.ac.uk/legislation/docs/COP_Research.pdf)**

UNIVERSITY OF BIRMINGHAM APPLICATION FOR ETHICAL REVIEW	*OFFICE USE ONLY:* Application No: Date Received:

1. TITLE OF PROJECT

Influences of low back pain on sensory integration and motor control during activities of daily living

2. THIS PROJECT IS:

University of Birmingham Staff Research project ☒
University of Birmingham Postgraduate Research (PGR) Student project ☐
Other ☐ (Please specify):

3. INVESTIGATORS

a) PLEASE GIVE DETAILS OF THE PRINCIPAL INVESTIGATORS OR SUPERVISORS (FOR PGR STUDENT PROJECTS)

Name: Title / first name / family name	Professor Deborah Falla
Highest qualification & position held:	Chair in Rehabilitation Science and Physiotherapy
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

Name: Title / first name / family name	Dr. Alessandro Marco De Nunzio
Highest qualification & position held:	Research Fellow
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

Name: Title / first name / family name	Dr. Alison Rushton
Highest qualification & position held:	Senior Lecturer
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

Name: Title / first name / family name	Dr. Nicola Heneghan
Highest qualification & position held:	Lecturer
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

b) PLEASE GIVE DETAILS OF ANY CO-INVESTIGATORS OR CO-SUPERVISORS (FOR PGR STUDENT PROJECTS)

Name: Title / first name / family name	Nicola Middlebrook
Highest qualification & position held:	MRes student
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

c) In the case of PGR student projects, please give details of the student

Name of student:		Student No:	
Course of study:		Email address:	
Principal supervisor:			

4. ESTIMATED START OF PROJECT Date: 01/01/2017

ESTIMATED END OF PROJECT Date: 31/12/2019

5. FUNDING

List the funding sources (including internal sources) and give the status of each source.

Funding Body	*Approved/Pending /To be submitted*
To be funded from the start-up of Prof. Deborah Falla	Approved

If you are requesting a quick turnaround on your application, please explain the reasons below (including funding-related deadlines). You should be aware that whilst effort will be made in cases of genuine urgency, it will not always be possible for the Ethics Committees to meet such requests.

6. SUMMARY OF PROJECT

Describe the purpose, background rationale for the proposed project, as well as the hypotheses/research questions to be examined and expected outcomes. This description should be in everyday language that is free from jargon. Please explain any technical terms or discipline-specific phrases.

Low back pain (LBP) is a major clinical problem with substantial socio-economic impact. Whilst some individuals seek medical and therapeutic interventions for pain relief, many more live with LBP where there is no specific cause or known pathology, termed non-specific LBP. Current diagnosis of LBP and optimal therapies are insufficient, and knowledge concerning the interaction between musculoskeletal pain and motor performance being incomplete (Hong, Reed, Novick, & Happich, 2013; Kalichman, Kim, Li, Guermazi, & Hunter, 2010; Parsons & Courtney, 2014; Vos et al., 2012). Many studies in this field have been performed under static conditions which do not represent patients' daily-life routines (Gallagher & Callaghan, 2015, 2016; Mazaheri, Coenen, Parnianpour, Kiers, & van Dieen, 2013). In the present project a series of activities of daily living (ADL) will be analysed using a comprehensive assessment.

Biomechanics of body segments (kinematic and kinetic evaluation), synergistic motor outcome (via high-density electromyography recordings) (EMG) and cortical activity (via electroencephalography) (EEG) will be studied in people with LBP and age-and gender matched control participants.

The general aim of the project is to understand how the brain orchestrates sensory-motor integration and motor control to manage pain. The specific aim of this project is to study the association between changes in motor control abilities and different pain domains (in line with the Initiative on Methods, Measurement, and Pain Assessment in Clinical Trials - IMMPACT - recommendations (Dworkin et al., 2005; Gewandter et al., 2014) that including physical functioning, pain quality, pain intensity and emotional functioning). To date, changes in motor control abilities and different pain domains have never been quantified systematically together during ADL.

The project is divided into three separate studies which focus on different motor tasks

1. **Postural control in normal and challenged conditions (voluntary holding of a steady inclined position)**
2. **Gait Initiation and Sudden Unplanned Gait Termination**
3. **Walking along curvilinear path and turning strategies**

SUMMARY OF STUDY 1

1. Postural control in normal and challenged conditions

Working Hypotheses

1. The postural effects, induced via proprioceptive stimulation, are different in LBP compared to healthy participants likely due to a change in body schema.
2. LBP participants will display a limitation in reaching challenging postural conditions (voluntary holding of a steady inclined position) as expression of inability to voluntarily switch to a new postural set

Background working hypothesis 1

Postural control to maintain an upright stance is one of the most important and basic requirements in the daily life of humans. The sensory inputs involved in postural control include visual and vestibular inputs, as well as proprioceptive and tactile somatosensory inputs. These multisensory inputs are integrated to represent the body state (*body schema*) and as reference to generate and control motion (Maurer, Mergner, & Peterka, 2006; Schweigart & Mergner, 2008).

Posture can be tested by measuring movement of the body's center of mass relative to the base of support (controlled by the Center of Pressure (CoP) movements (Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998) in standing under the instruction to stand relaxed or minimize movement, referred as postural sway.

Limiting postural sway requires adequate trunk control, since any rotation around the ankle joints (considering the standing body as an inverted pendulum controlled at ankle joint (Morasso & Schieppati, 1999; Winter et al., 1998) will induce variation in gravitational moments around the spine that have to be controlled by trunk musculature to maintain trunk alignment (Creath, Kiemel, Horak, Peterka, & Jeka, 2005; Hodges, Gurfinkel, Brumagne, Smith, & Cordo, 2002; Oullier, Bardy, Stoffregen, & Bootsma, 2002). In addition, small deviations from the single inverted pendulum approximation do occur, as postural sway comprises trunk movements that are coordinated with movements of the lower extremities to reduce excursion of the body's center of mass (Hodges et al., 2002; Oullier et al., 2002). The latter case specifically applies when balance needs to be achieved under dynamic, critical or unstable conditions (Courtine, De Nunzio, Schmid, Beretta, & Schieppati, 2007; De Nunzio, Nardone, Picco, Nilsson, & Schieppati, 2008; De Nunzio, Nardone, & Schieppati, 2005; Mientjes & Frank, 1999; Schieppati, Hugon, Grasso, Nardone, & Galante, 1994).

Niels and Sinnott in 1991 (Nies & Sinnott, 1991) were the first to investigate balance control in patients with LBP, by measuring CoP movements. Subsequently, many comparable studies have been published and a recent review concluded that there is consistent evidence that LBP coincides with increased sway amplitude and/or sway velocity (Ruhe, Fejer, & Walker, 2011).

However, there are no previous studies investigating whether LBP alters the integration of proprioceptive inflow to create their body schema and manage posture.

Sensory information conveyed along afferent fibres from muscle proprioceptors plays an important role in the control of posture in humans (Kavounoudias, Gilhodes, Roll, & Roll, 1999; Kavounoudias, Roll, & Roll, 1998; Roll, Vedel, & Roll, 1989; Schieppati & Nardone, 1999) and jointly contribute to the body schema formation (Roll, Vedel, & Roll, 1989). Tendon vibration almost selectively activates muscle spindle primary endings and elicits a discharge in the fast conducting large-diameter group Ia afferent fibers (Roll & Vedel, 1982; Roll, Vedel, & Ribot, 1989) thereby providing a means to influence proprioceptive inflow. Thus we will evaluate whether proprioceptive information is differently integrated to balance the body in people with LBP versus healthy controls.

Methods working hypothesis 1

To evaluate the 1st working hypothesis, we will apply unilateral vibration to various regions of the body (see methods for details) during a quiet stance condition with eyes open and eyes closed.

Surface EMG will be recorded from the lumbar erector spinae, selected lower limb and neck muscles bilaterally. EEG as well as CoP movements and ankle torque will be recorded.

We will compare the biomechanical differences (especially kinetic: CoP movements and ankle torque) between people with LBP and age and gender-matched participants in exploiting proprioceptive input subserving posture and correlate the differences with measures of motor control (level of muscle activation variability determined from the EMG recordings) and its cortical signature (EEG local field desynchronizations in sensorimotor and parietal cortex (Wagner, Makeig, Gola, Neuper, & Muller-Putz, 2016).

Background working hypothesis 2

To accomplish the 2nd working hypothesis, we will evaluate how balance is maintained under a challenged condition characterized by voluntarily holding a steady, inclined posture, up to the limit of stability (McCollum & Leen, 1989; Schieppati et al., 1994). This condition implies both greater activation of postural muscles than in normal stance to counteract the increased momentum of gravity, and conscious descending input to the spinal cord.

A previous study (Schieppati et al., 1994) has assessed this challenged stance condition in young and elderly healthy people, and in idiopathic parkinsonians; finding that while sway area was minimal during normal stance, it increased progressively when the subjects leant forward or backward showing a clear fine-tuned function of body support from the tibialis anterior and soleus muscles, and sway control from extensor and flexor digitorum muscles. Age influenced the extent of Antero-Posterior (A-P) leaning without changing the relationship between sway area and A-P displacement, while people with Parkinson's showed impairment in achieving this challenged stance condition, still maintaining the same relationship between muscle activity and body inclination (indicating a preserved feedback mechanism reflexly controlling balance (De Nunzio et al., 2008)). These previous findings highlight that posture inclinations represent a clear different postural set as people with Parkinson's fail to integrate normal afferent input into a novel reference system (the critical posture, deliberately assumed).

Methods working hypothesis 2

Based on these premises we will use the challenged posture test to study the ability of people with LBP to modulate the gain of different postural loops voluntarily reaching a new postural set.

The same experimental set-up of the previous project session will be used to extract information regarding motor control and its neural correlates in switching across different postural sets.

SUMMARY OF STUDY 2

2. Gait Initiation and Sudden Unplanned Gait Termination

Working Hypotheses

1. LBP participants will exhibit a modification of the Anticipatory Postural Adjustments during gait initiation compared to healthy participants as pain may influence the feedforward subcortically-mediated motor actions accomplished during this task.
2. LBP will be associated with an alteration of the Compensatory Postural Adjustments executed during a sudden unplanned gait termination since pain may impair the ability to control a startle response.

Background working hypothesis 1

The identification of biological factors that play a role in the persistence of symptoms is vital for the development of interventions to treat LBP. A plausible biological mechanism that may impede LBP recovery is the control of postural perturbations by the central nervous system (CNS). Ineffective control of postural perturbations increases the risk of excessive forces being experienced by passive structures of the spine (Cholewicki & McGill, 1996; Panjabi, 1992), contributing to the persistence of LBP. During ADL, people may experience postural perturbations in the form of self-initiated movements, standing on a moving bus, or being hit by an external object. Anticipatory (APAs) and compensatory (CPAs) postural adjustments are alterations in muscle activity by the CNS to control forces imparted on the body by postural perturbations (Tisserand et al., 2015; Viton et al., 2000). APAs can be observed prior to a predictable perturbation and serve to minimise the perturbation's effect (MacKinnon et al., 2007), while CPAs are observed following a perturbation and are a mechanism to re-establish postural equilibrium (Alexandrov, Frolov, Horak, Carlson-Kuhta, & Park, 2005; Park, Horak, & Kuo, 2004).

A well-studied example of APAs occurs during the transition from stationary standing to stepping forward to initiate gait (Crenna & Frigo, 1991; Rogers, Kukulka, Brunt, Cain, & Hanke, 2001). These APAs involve a sequence of muscle activations and changes in the ground reaction forces (GRFs)

that move the net CoP beneath the feet backward and toward the initial swing limb (see Fig. 1). This sequence of activity produces the forces and moments necessary to propel the body forward and toward the single-stance limb for the regulation of whole body balance and posture before and during initiation of the voluntary step.

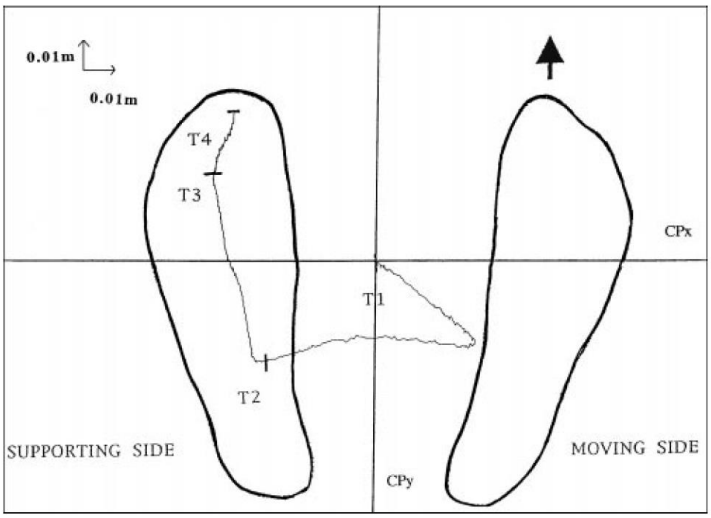


Figure 1 - adapted from Viton et al. 2000

A variety of studies in animals and humans have investigated the neural mechanisms contributing to the generation of the APAs that precede and accompany voluntary movement concluding that the putative regions involved in the control of posture and the intended movement are organized separately (Schepens & Drew, 2003, 2004). Based on the findings of lesion studies, Massion (Massion, 1992) proposed that the neural networks responsible for the control of APAs are organized subcortically. This idea is supported by studies in quadrupeds showing that the pontomedullary reticular formation is involved in the control of posture through brain stem–spinal pathways that may be engaged through motor corticofugal connections (Drew, Prentice, & Schepens, 2004; Matsuyama & Drew, 1997). Thus the motor cortical command for a goal directed movement might include feedforward signals for generating the postural adjustments that anticipate and accompany movements (Massion, Alexandrov, & Frolov, 2004; Massion, Ioffe, Schmitz, Viallet, & Gantcheva, 1999). A previous extensive study (MacKinnon et al., 2007) confirms there is an initial phase of movement preparation during which the APA-stepping sequence was progressively assembled, and that this early preparation did not involve the corticomotor pathways which only contribute to the following voluntary initiation of the prepared APA-stepping sequence. These findings are consistent with a feedforward mode of neural control whereby the motor sequence, including the associated postural adjustments, is prepared before voluntary movement.

Methods working hypothesis 1

Preparation of APAs prior to stepping will be studied in people with LBP with the aim of testing the influence on feedforward subcortically-mediated motor actions.

We hypothesise that the APA-stepping sequence could be differently assembled in people with LBP leading to a generation of an impaired voluntary first step action during walking.

Kinetics and kinematics of the body segments, lower limb and trunk muscle activity as well as cortical involvement in voluntary generation of the first walking step will be acquired and analysed. Variability of the onset timing of APAs and the accompanying EMG activity will be correlated with the onset of the volitional first walking step movement to explore if LBP can alter the independency between plan and control of APA and voluntary motor actions.

Background working hypothesis 2

Sudden unplanned gait termination is a dynamic motor task. We stop abruptly in response to unexpected events, such as a car not stopping at a pedestrian crossing, a door closing, an alarming sound, and so on.

Sudden stopping or termination of gait requires abrupt deceleration of the forward progression of the body and the assumption of a stable posture (Hase & Stein, 1998). This task may be particularly

demanding individuals with LBP, as it reduces their gait stability and could even lead to an increased incidence of falls (Gryfe, Amies, & Ashley, 1977; Stenhagen, Ekstrom, Nordell, & Elmstahl, 2013).

Sudden stopping is accomplished in a single step, always with one foot forward (leading leg) and the other back (trailing leg) (Sparrow & Tirosh, 2005). The trailing leg decreases the acceleration and lowers the centre of mass (CoM) (extension synergy), while the leading leg increases the braking force and further decelerates the CoM (flexion synergy (Hase & Stein, 1998; O'Kane, McGibbon, & Krebs, 2003). If the effect of these two mechanisms is too weak or they intervene too late in the step cycle, the momentum of the CoM will carry the body forward over the extended leading leg. This will also cause the subject to rise on his toes, thus converting some kinetic energy into potential energy, or moving the arms and rotating the body about the vertical axis (O'Kane et al., 2003; Oates, Frank, & Patla, 2010). In any of the previously reported strategies the trunk and its mass play a major role in storing and reducing the CoM momentum.

Moreover, from a neurophysiological perspective a sudden and unexpected gait termination motor action could possibly be characterised as a startle reaction. Therefore, we could expect shorter reaction times than the calculated minimum time for processing of sensory information at the cerebral cortex and therefore an APA followed by a CPA with the first triggered entirely by activity at subcortical levels (probably involving the startle circuit).

Methods working hypothesis 2

In this part of the project, we will explore the hypothesis that LBP may negatively affect a person's ability to abruptly stop walking, in other words, their ability to compensate for the imbalance due to the mechanical perturbations in the sagittal plane and that pain could lead to a different assembly and release of the APA compared to the CPA strategy.

We hypothesise that, in order to compensate for instability in the sagittal plane, they may show a longer and multi-step gait termination strategy and impaired transfer of the forward momentum from the sagittal to the frontal plane. Furthermore, compared with healthy participants, patients may be unable to adequately coordinate trunk movements in order to maintain whole body stability, as well as they may be unable to execute an effective lower limb flexion–extension pattern in order to scale the braking forces needed to decelerate the forward momentum.

This objective will be obtained using the same experimental set-up reported above to study APAs during gait initiation.

SUMMARY OF STUDY 3

3. Walking along a curvilinear path and turnings strategies

Working Hypothesis

1. LBP participants will exhibit an impaired ability to walk along curved trajectory as trunk control and stability are likely affected by pain

Background

Human walking has been extensively studied from kinematic, kinetic and physiological viewpoints (Barker, Craik, Freedman, Herrmann, & Hillstrom, 2006; Coutts, 1999; Ivanenko, Poppele, & Lacquaniti, 2006; Sousa & Tavares, 2015). However, investigations have frequently isolated the walking person from his/her natural context, by studying gait in limited conditions, such as straight-ahead walking, and often on a treadmill.

Even though locomotion along a straight path may represent an easy task for a normal human, it is rarely encountered in everyday life. Often, humans are faced with changes in path direction, which can be either unexpected or anticipated in advance. In both of the cases, the central nervous system (CNS) must abdicate to the symmetry of the locomotion apparatus, which seems to be adapted to straight-ahead walking (Rossignol, 1996; Rossignol et al., 1996).

Walking in a curved path may thus involve a trade-off between automatic forward progression and voluntary rotation of the body (Domenici, Jamon, & Clarac, 1998; Labruyere & van Hedel, 2012),

thereby resulting in the production of smooth, adapted trajectories (Hase & Stein, 1999). Constraints of equilibrium, already present during straight-ahead locomotion (Cavagna & Margaria, 1966; Pozzo, Papaxanthis, Stapley, & Berthoz, 1998), also challenge the CNS during curved walking (Godi, Nardone, & Schieppati, 2010; Guglielmetti, Nardone, De Nunzio, Godi, & Schieppati, 2009; Thigpen, Light, Creel, & Flynn, 2000).

Walking along curved trajectories implies a different spatiotemporal pattern of muscle activation than straight walking. This is due to the constraints of the task (Courtine & Schieppati, 2003a, 2003b). Stride length of the inner leg (closer to the centre of curvature) is necessarily shorter than that of the outer leg, because the distance between the feet is not annulled during curved walking and the step frequency is the same for both legs. Swing velocity is greater for the outer than the inner foot. The inner foot is placed on the floor at a greater angle than the outer foot with respect to the trajectory. Stance phase duration is shorter in the outer than inner leg. Ground reaction force is greater for the outer foot at heel strike and toe-off, whereas it is greater for the inner foot during the mid-stance phase (Turcato, Godi, Giordano, Schieppati, & Nardone, 2015). Trunk roll is greater towards the inner than the outer side, whereas it is symmetrically and alternately distributed during straight walking. Mediolateral displacement of body centre of mass toward the supporting leg is shifted inwards, to create the centripetal force that keeps the body moving along the circular path (Courtine & Schieppati, 2003a, 2003b; Turcato et al., 2015). These kinematic and dynamic constraints require an adapted mode of control. Amplitude and timing characteristics of the muscles' activation are significantly associated with the spatial and temporal adaptations to curvilinear locomotion (Courtine, Papaxanthis, & Schieppati, 2006; Courtine & Schieppati, 2004).

Methods

Given i. the substantial complexity of the changes required to smoothly accomplish locomotion along a curved trajectory and ii. the importance of trunk control, mainly operated via proprioceptive inflow integration from paraspinal muscles (Courtine et al., 2007; Schmid, De Nunzio, & Schieppati, 2005), we will investigate the capacity of people with LBP to walk along a 180° curved path.

We hypothesise that LBP could induce poor posturokinetic coordination and affect biomechanics of gait to some extent, showing an impaired control compared to walking straight-ahead or compared to asymptomatic subjects.

Variability of paraspinal muscle activity will be studied via high-density EMG, in conjunction lower limb and neck muscle activity. Sensorimotor and parietal cortex involvement will be studied as controlling an automatic/stereotyped motor task (CPG generation) superimposed on a voluntary synergistic motor modulation to control body rotation (gait adaptation) (Wagner et al., 2016).

7. CONDUCT OF PROJECT

Please give a description of the research methodology that will be used

Design: Cross-sectional.

All studies will be conducted in the human movement laboratory of the School of Sport, Exercise and Rehabilitation Sciences.

For each study, participants will attend a single laboratory session. All measurements will be done as follows:

Study 1: **Postural control in normal and challenged conditions**
Postural assessment will be performed using two Force Platforms (BTS Bioengineering, Italy) embedded in the floor and positioned at floor level to avoid vivid edges. The quiet upright posture assessment will be performed in order to detect the instant position of the Center of Pressure (CoP). Participants will be asked to stand barefoot on the force platform (one foot on each force platform) with their feet spaced 17 cm apart (measured between heels) and a 14° angle between feet (McIlroy & Maki, 1997), with arms at their sides looking at a visual target adjusted to eye-level height, 40 cm in front. All participants will receive the same instructions: to keep their gaze fixed on the visual target, standing for at least 40 s. In order to ensure accuracy and reiteration across trials, foot positioning will be marked on the platform. During the challenged condition trials the participants will be asked to lean forward or backward as far as possible. To assure safety, an experimenter will stand close to the participant preventing any possible fall, which in any case would be very unlikely.

Inclinations will be accomplished without lifting toes or heels and within minimal bending at the hip or knees, and keeping the trunk as straight as possible.
Eyes-open (EO), and eyes-closed (EC) conditions will be recorded, and 6 consecutive trials (Pinsault & Vuillerme, 2009) (3 EO, 3 EC randomly assigned) will be collected. In order to avoid possible fatigue, a 1-minute rest will be given between trials.

The CoP displacement will be analysed off-line from the unfiltered platform signal by using two different parameterisations techniques (Baratto, Morasso, Re, & Spada, 2002): i) global parameterisation which numerically expresses the overall size of the sway patterns, in time and frequency domains; and ii) structural parameterisation which identifies subunits of posturographic data related to the underlying motor control process.
In order to compute structural parameters, a Sway Density Plot (SDP) will be calculated by counting the number of consecutive samples of the posturographic trajectory which, for each time instant, fall within a test circle (Ø 2.5 mm) (Baratto et al., 2002). SDP describes a regular series of peaks and valleys. Peaks correspond to time instants in which the ankle torque is relatively stable and is associated to the feed-forward control actions (motor commands); valleys are related to time instants in which the ankle torque rapidly shifts between two consecutive stable points.
The main reason for clinical interest in the analysis of the CoP signal is the fact that its time structure can reveal something of the postural control mechanism and its pathological modifications, because the CoP signal is proportional to the ankle torque (Morasso & Sanguineti, 2002; Morasso & Schieppati, 1999). This torque is the combination of the descending motor commands as well as the mechanical properties of the muscles acting around the ankle. The descending motor commands modulate, at the same time, the ankle torque and the ankle stiffness (Baratto et al., 2002).
The following indices, will be computed for each trial and condition (EO, EC):

- the Sway Path (SP) of the CoP (integrating the instant velocity of the CoP over the total recording time);
- the frequency bandwidth (including the 80% of the amplitude spectrum area (FB1) (Baratto et al., 2002)), separately computed for the antero-posterior (A-P) and medio- lateral (M-L) CoP movements direction;
- the Mean amplitude of the Peaks (MP) of the Sway Density Plot (SDP) - MP is an a-dimensional value which estimates the posture stability degree;
- the Mean Distance (MD) between two consecutive peaks of the SDP (for details see (Baratto et al., 2002)) – it represents the amplitude of the feed-forward control actions (motor commands);
- the Median CoP position along M-L direction will be calculated as index of participants' asymmetrical weight distribution on the feet.
- The Median CoP position along A-P direction will be calculated as index of participants' ability in weight shifting during critical stance condition trials.

Studies 2 and 3: **Gait Initiation, Walking along curvilinear path and Gait Termination**

The participants will undergo a kinematic evaluation of walking with an infrared camera based optoelectronic system (BTS Bioengineering, Italy). Participants, starting with their feet on the force platforms, will be asked to walk barefoot at their usual cadence, along a 6-m rectilinear walkway, making a continuous turn, following a curvilinear path with 120 cm radius of gyration and walk back to the starting point. A set of at least three repetitions will be acquired. A 2 minutes rest between walking trials will be given to avoid participant exhaustion.
Synchronised with lower limb joint kinematics the coronal and sagittal walking plane will be videotaped. Videotape archiving of the participant's gait is advisable for a number of reasons. For example a videotape record allows a close examination of abnormal foot dynamics such as varus/valgus and mid-foot abnormalities. A videotape of the participant, not encumbered in any way by markers, provides the researcher with an overall or "global" view of the participant and additional documentation for later presentation and discussion. Camera height will be adjusted to exclude face visualisation from the video.
In addition, anthropometric measurements will be taken which include the participant's height, weight and leg length. Data used for the estimation of the joint center locations will be collected, i.e. the knee and ankle widths (as seen in the coronal plane of the limb), the distance between right and left pelvic anterior superior iliac spine (ASIS) and the vertical distance in the sagittal plane of the supine participant between ASIS and the greater trochanter (with the femur rotated such that the greater trochanter is oriented as lateral as possible).
The optoelectronic system consists of 8 infrared cameras (100 Hz sampling rate) that track the 3D motion of passive retroreflective markers. All data will be acquired using BTS SMART Capture software and saved to disk for off-line analysis.

The retroreflective 22 marker set used in the lab will be placed according to the protocol described in Davis et al. (R. B. Davis, Ounpuu, Dennis, & Gage, 1991). The markers will be placed on the participant according to the following specifications:
Trunk: 1. right acromion process, 2. left acromion process, 3. 7th cervical spinous process.
Pelvis: 1. right ASIS, 2. left ASIS, 3. over the 5th lumbar spinous process.
Thigh: 1. right greater trochanter, 2. left greater trochanter, 3. right lateral femur epicondyle, 4. left lateral femur epicondyle, 5. along the right femur axis oriented so that the longitudinal axis of the thigh lies in the plane formed by the three markers, 6. along the left femur epicondular axis .
Shank: 1. right head of fibula, 2. left head of fibula, 3. right malleolus, 4. left malleolus, 5. along the right fibula axis oriented so that the longitudinal axis of the shank lies in the plane formed by the three markers, 6. along the left fibula axis.
Foot: 1. right toe, 2. left toe, 3. on the lateral aspect of the right foot at the fifth metatarsal head, 4. on the lateral aspect of the left foot at the fifth metatarsal head, 5. right heel (positioned so that the heel-toe marker vector is parallel to the sole of the foot), 6. left heel (positioned so that the heel-toe marker vector is parallel to the sole of the foot).

Electomyographic (EMG) assessment
Surface EMG measurements will be acquired during walking tests, synchronized with kinematic and kinetic (force) data. Surface electrodes for EMG measurements will be located and placed on the participant following a standard guideline provided by the SENIAM project (www.seniam.org). The SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) is a European concerted action in the Biomedical Health and Research Program (BIOMED II) of the European Union.
Bipolar Ag-AgCl surface electrodes will be used to record EMG bilaterally from:
- Tibialis Anterior (TA)
- Soleus (Sol)
- Gastrocnemius Medialis (GasM)
- Tibialis Posterior (TP),
- Erector Spinae (ES),
- Peroneus Longus (PL),
- Biceps Femoris long head (BF),
- Tensor Fascia Latae (TF)
- Vastus Lateralis (VL).

A completely wireless EMG acquisition system will be used (BTS Bioengineering, Italy). Each skin site will be shaved with disposable razors and cleaned with alcohol before electrode placement (Hermens et al., 1999; Perotto, 1994). All data will be acquired at 1,000 Hz using BTS EMG Analyser software and saved to disk for off-line analysis.

High Density Surface EMG
Surface EMG signals will be detected with semi-disposable adhesive grids of electrodes (OT Bioelettronica, Torino, Italy) placed over the lumbar erector spinae. Each grid consists of 8 rows and 8 columns of electrodes (1-mm diameter, 10-mm inter-electrode distance in both directions). To characterize the spatial distribution of muscle activity, the following variables will be extracted from the bipolar signals: Root mean square (RMS) and mean frequency (MF) averaged over all signals and the two coordinates of the centroid of the root mean square map (x and y-axis coordinates for the medial-lateral and cranial-caudal direction, respectively (Falla, Arendt-Nielsen, & Farina, 2008), (Falla, Gizzi, Tschapek, Erlenwein, & Petzke, 2014).

Kinematics and EMG data reduction and analysis
Synchronised kinematics and EMG acquisition and data processing will be performed using Analyser software (BTSS.p.a.) and custom written routines in LabView National Instruments software.

Kinematics
After the walk is complete and all camera information are collected, the two-dimensional coordinates of the centroid of each marker image will be determined for each frame of optoelectronic camera data. Three dimensional marker coordinates will be computed stereometrically from the two dimensional camera data. The instantaneous orientation of an orthogonal, marker-based, embedded coordinate system will be determined for the trunk and pelvis and each thigh, shank and foot segment. The marker-based embedded coordinate systems for the thigh, shank and foot will then be realigned with the instantaneous, joint center-based, embedded coordinate systems. The angular offset values used in this realignment process will be computed from the standing data that will be collected prior to the walking test. Finally, three dimensional limb rotation angles will be calculated from the embedded coordinate system information.
The analysed Kinematic indexes will be:
- temporal parameters of walking cycle (R. B. Davis et al., 1991)

- stance and swing phase duration (% stride cycle) for right and left side,
- double stance phase duration (% stride cycle) for right and left side,
- stance and swing phase duration (time duration of the stride cycle) for right and left side,
- time duration of the stride phase (s) for right and left side,
- walking cadence (step/minutes)

- spatial parameters of walking cycle (R. B. Davis et al., 1991)
  - step length (m) for right and left side,
  - stride velocity (m/s) for right and left side,
  - swing velocity (m/s) for right and left side,
  - stride length (m) for right and left side,
  - step width (m) for right and left side
  - walking velocity (m/s)
- three dimensional joint rotation during stride cycle along sagittal, coronal and horizontal anatomical plane, for right and left side (R. B. Davis et al., 1991)
  - pelvis rotation (deg),
  - hip rotation (deg),
  - knee rotation (deg),
  - ankle rotation (deg),
- elevation angles for right and left side (Borghese, Bianchi, & Lacquaniti, 1996; Ivanenko, d'Avella, Poppele, & Lacquaniti, 2008; Lacquaniti, Grasso, & Zago, 1999)
  - thigh (deg)
  - shank (deg)
  - foot (deg)

EMG

The EMG signals will be off-line band-pass filtered (fourth-order zero-lag Butterworth digital filter, bandwidth 20 – 400 Hz) to attenuate DC offset, motion artefacts, and high-frequency noise (Hermens et al., 1999). The filtered signals will be full-wave rectified and low-pass filtered (fourth-order zero-lag Butterworth digital filter, cut-off frequency 10 Hz) to obtain the muscle activation patterns. To facilitate comparisons between participants and among different walking speeds, the EMG from each muscle will be normalized to its peak value from self-selected walking and resampled at each 1% of the gait cycle (Clark, Ting, Zajac, Neptune, & Kautz, 2010).

Matrix Factorisation Algorithm

We will use a version of probabilistic ICA (pICA) that, in addition to allowing estimates of the noise for each data dimension, also allowed the basis vectors and activation coefficients to be constrained to be nonnegative (Hojen-Sorensen, Winther, & Hansen, 2002; Kolenda, Sigurdsson, Winther, Hansen, & Larsen, 2002) http://mole.imm.dtu.dk/toolbox/menu.html.

The correct number of basis vectors will be indicated by an ad hoc procedure based on variance and likelihood curves. We will apply the above algorithm, varying the number of bases from one to eight. We then calculate the amount of variance and the likelihood of the data set explained by each algorithm with a particular number of bases. However, several studies consistently showed that the EMG activity of trunk and leg muscles during human adult locomotion is adequately reconstructed as a linear combination of four to five basic patterns, each one timed at a different phase of the gait cycle (Cappellini, Ivanenko, Poppele, & Lacquaniti, 2006; Clark et al., 2010; B. L. Davis & Vaughan, 1993; Gizzi, Nielsen, Felici, Ivanenko, & Farina, 2011; Ivanenko, Cappellini, Dominici, Poppele, & Lacquaniti, 2005; Ivanenko, Cappellini, Poppele, & Lacquaniti, 2008; Ivanenko, Poppele, & Lacquaniti, 2004; McGowan, Neptune, Clark, & Kautz, 2010; Olree & Vaughan, 1995; Patla, 1985). The average shape of each pattern, once it is time-normalized to stride duration, is little affected by changes in walking speed (Ivanenko et al., 2004), direction (walking backwards versus walking forwards, (Ivanenko, Cappellini, et al., 2008)), loading or unloading of the limb and body (McGowan et al., 2010), or changes in locomotion mode (running versus walking; (Cappellini et al., 2006)). The similarity of the average waveforms irrespective of walking or running speed suggests that each command is shaped relative to the overall duration of the gait cycle, so that the resulting muscle activations have a short duration at high speeds and a longer duration at low speeds. Similarity of the average waveforms will be tested according with walking direction conditions (rectilinear or curvilinear).

Activation characteristics contributing to reduced complexity

An examination of the characteristics of muscle activation responsible for possibly reduced locomotor output complexity (Falla et al., 2014) will be realised. LBP participants will be separated into groups based on the number of modules required for EMG reconstruction (2, 3, or 4 modules), performing the Matrix Factorization (pICA) analysis assuming four modules for all of the participants. This procedure will assess how the muscle weightings differed among groups and how activation profiles differed among modules within the same group. The muscle weightings for each

module will be correlated across groups to quantify the similarity (i.e., module 1 across groups, module 2 across groups, etc.). High correlations indicate similar module composition. Within each group, correlations of activation timing profiles between modules were computed to assess whether modules are independently active. High correlations indicate a lack of independent module activation.

EMG magnitude
To assess the potential effect of the EMG magnitude on the number of modules identified, raw EMG in millivolts from each muscle will be averaged by condition (i.e., rectilinear or curvilinear) over all the gait cycles for each participant for the respective walking condition. The values from all muscles will be averaged together to obtain a single composite measure for each walking condition of each participant.

Correlation between kinematics and modules of EMG reconstruction
The trajectories of the body Center of Mass (COM) and feet are highly regular and repeatable in human gait (Winter, 1991). They are determined by the combined rotation and translation of the lower limb segments. The pelvis, thigh, shank and foot oscillate back and forth relative to the vertical with a similar waveform, time-shifted across different segments (Bianchi, Angelini, Orani, & Lacquaniti, 1998; Borghese et al., 1996), and in so doing they carry the trunk and feet along. When the segment elevation angles are plotted one versus the others, they describe regular loops constrained close to a plane common to both the stance and swing phase (Borghese et al., 1996; Ivanenko, d'Avella, et al., 2008; Lacquaniti et al., 1999). The specific orientation of the planar covariance reflects the phase relationships between the segment elevation angles, and therefore the timing of the inter-segmental coordination (Bianchi et al., 1998).
The planar covariance in walking, with the corresponding muscle activation patterns inserted at the time of occurrence along the gait loop will be also calculated to study the phase coupling between the elevation angles and the muscles activation patterns along rectilinear and curvilinear walking.

The same analysis procedures will be adopted on kinematic, kinetic and EMG data selected around the gait initiation and termination phase.

Kinematic (motion), kinetic (force and torque) and EMG acquisition will be realised in one single session for LBP participants and healthy volunteers.

Pain Domains Assessment
Quantitative sensory tests will be performed including pressure pain thresholds and thermal pain thresholds (Rolke, Baron, et al., 2006) over regions of the lumbar spine and at a remote site (non-dominant hand). Pressure pain thresholds will be measured over locations distributed across the lumbar region using a pressure algometer (Somedic, CE). Participants here simply indicate when they perceive pain for the first time during pressure stimulation with slowly increasing intensity (50 kPa/sec). Stimulation will stop with the report of pain. Thermal pain thresholds will be measured with a Thermal Sensory Analyzer II, Medoc, Israel (CE certification enclosed). Temperature change will stop with the report of pain.

Healthy Controls: Self Reports
Questionnaire data as described below will be obtained from the controls:

- SF-12 Health Survey: A measure of the general health status of the patient (Brazier et al., 1992)
- Depression, Anxiety, Stress Scales (DASS): A self-rating measure of depression, anxiety and stress (Lovibond & Lovibond, 1995)
- International Physical Activity Questionnaires (IPAQ) to measure physical activity of participants (Booth, 2000)

LBP participants Self Reports
Questionnaire data as described below will be obtained from the participants:

- Back pain questionnaire: Questions pertaining to back pain area, intensity and duration.
- International Physical Activity Questionnaires (IPAQ) to measure physical activity of participants (Booth, 2000)
- SF-12 Health Survey: A measure of the general health status of the patient (Brazier et al., 1992)
- The Van Korff scale (VKS): A measure to grade severity of chronic pain (Von Korff, Ormel, Keefe, & Dworkin, 1992)
- The Pain Catastrophizing Scale (PCS): A measure of catastrophic thinking related to pain

(Osman et al., 1997).
- Depression, Anxiety, Stress Scales (DASS): A self-rating measure of depression, anxiety and stress (Lovibond & Lovibond, 1995)
- The Oswestry Disability Index will be used to assess pain-related disability specifically related to LBP (7 items (Fairbank & Pynsent, 2000))
- Fear Avoidance Believe Questionnaire (Waddell, Newton, Henderson, Somerville, & Main, 1993)

Additionally, participants will report the area where the pain is felt by completing a pain drawing through sketch software on an iPad.

Multifactorial fall risk assessment will be realised using the following tools:
- Timed Up and Go test (TUG) (Okubo, Schoene, & Lord, 2016)
- Tinetti Performance Oriented Mobility Assessment (POMA) (Sterke, Huisman, van Beeck, Looman, & van der Cammen, 2010; Thomas & Lane, 2005)
- Activities-specific Balance Confidence (ABC) Scale (Lajoie & Gallagher, 2004)
- Tinetti Falls Efficacy Scale as measure of fear of falling (Hauer et al., 2010; Tinetti et al., 1990)

8. DOES THE PROJECT INVOLVE PARTICIPATION OF PEOPLE OTHER THAN THE RESEARCHERS AND SUPERVISORS?

Yes ☒ No ☐

Note: 'Participation' includes both active participation (such as when participants take part in an interview) and cases where participants take part in the study without their knowledge and consent at the time (for example, in crowd behaviour research).

If you have answered NO please go to Section 18. If you have answered YES to this question please complete all the following sections.

9. PARTICIPANTS AS THE SUBJECTS OF THE RESEARCH

Describe the number of participants and important characteristics (such as age, gender, location, affiliation, level of fitness, intellectual ability etc.). Specify any inclusion/exclusion criteria to be used.

30 healthy and physically active participants & 30 participants who experience chronic non-specific LBP (NSLBP) will be recruited for study 1. The same group of healthy and physically active participants as well as the 30 participants with non-specific LBP will undergo studies 2 and 3 as the 3 studies could be merged and realised into one single testing session. Resting periods among and within the sessions will prevent for any kind of possible muscular fatigue.

Inclusion criteria:

- Both females and males are eligible for the study.
- The age range will be restricted to 18- 65 years to limit age effects on physical measures of the lumbar region.
- LBP and control participants will have the capacity to give the consent at his/her own will.
- Pain-free participants will be included if they have no relevant history over the last three years of back or lower limb pain or injury that limited their function and/or required treatment from a health profession.
- Individuals with chronic NSLBP will be considered for the study.

The following definition for NSLBP is low back pain which is not related to serious pathology and/or does not have a specific cause (also known as simple or mechanical low back pain). Chronic refers to a sub type where back pain problem may have persisted at least 3 months and has resulted in pain on at least half the days in the past 6 months. If possible, participants should be willing to refrain from analgesic medication on the day of testing.

Exclusion criteria:

- Concurrent systemic, rheumatic or neuro-musculoskeletal disorders which may confound testing or are currently pregnant.
- Radicular low back pain or pain related to trauma, fractures, spinal stenosis.
- Participants with higher doses of opioids (> 30 mg of morphine equivalent dose) will be excluded.
- Participants under active management of LBP through specific medications prescribed by a GP, consultant or therapists (physiotherapist, osteopath, chiropractor) less than 3 months before the possible enrolment.

10. RECRUITMENT

Please state clearly how the participants will be identified, approached and recruited. Include any relationship between the investigator(s) and participant(s) (e.g. instructor-student).

Note: Attach a copy of any poster(s), advertisement(s) or letter(s) to be used for recruitment.

Healthy subjects will be recruited via poster advertisement at the:

- School of Sport, Exercise and Rehabilitation Sciences, College of Life and Environmental Sciences of the University of Birmingham

Research or staff members of the PI of the study will not be recruited as participants.

LBP participants will be recruited, via poster advertisement, from the community and population of staff and students at the University of Birmingham.

Interested volunteers will be asked to contact the PI through email / telephone or face to face.
All information regarding the experiment will be provided in the 'Participant Information Leaflet', that will be provided to interested volunteers.
The investigators involved in this project will explain the experiment procedures to the participants and answer any questions they may have.
The investigators' telephone and e-mail references will be provided on the 'Informed Consent' and 'Participant Information Leaflet'.
Data collection will take place in the School of Sport, Exercise and Rehabilitation Sciences, at the Human Movement Laboratory.

11. CONSENT

a) Describe the process that the investigator(s) will be using to obtain valid consent. If consent is not to be obtained explain why**.** If the participants are minors or for other reasons are not competent to consent, describe the proposed alternate source of consent, including any permission / information letter to be provided to the person(s) providing the consent.

All information regarding the experiment will be provided in the 'Participant Information Leaflet' (see attached) which will include a description of the study, inclusion and exclusion criteria, risk and benefits. The information about the study will also be provided verbally by an investigator.
Written informed Consent (see attached) will be obtained after the study has been explained and the volunteers have the opportunity to ask any questions they may have.

Note: Attach a copy of the Participant Information Sheet (if applicable), the Consent Form (if applicable), the content of any telephone script (if applicable) and any other material that will be used in the consent process.

b) Will the participants be deceived in any way about the purpose of the study? **Yes** ☐ **No** ☒

If yes, please describe the nature and extent of the deception involved. Include how and when the deception will be revealed, and who will administer this feedback.

12. PARTICIPANT FEEDBACK

Explain what feedback/ information will be provided to the participants after participation in the research. (For example, a more complete description of the purpose of the research, or access to the results of the research).

Each participating subject will receive a complete explanation of the study and its purpose following the measurements. Participants will be invited to leave their email address to receive the publication of the study results.

13. PARTICIPANT WITHDRAWAL

a) Describe how the participants will be informed of their right to withdraw from the project.

The participants' right to withdraw from taking or continuing the experiment will be clearly reported on the Consent Form and Information leaflet and will also be expressed verbally to the volunteers. Participants will be free to withdraw at any time during the experimental session and will have the right to withdraw their data from the study up to 1 month following data collection without giving a reason.

b) Explain any consequences for the participant of withdrawing from the study and indicate what will be done with the participant's data if they withdraw.

There are no consequences for dropping out or withdrawal from the study. In case of experiment interruption or withdrawal by the participant, personal data for participant identification and all the data acquired until the point of withdrawal will be deleted.

14. COMPENSATION

Will participants receive compensation for participation?

i) Financial **Yes**☒ **No** ☐

ii) Non-financial **Yes** ☐ **No** ☐

If **Yes** to **either** i) or ii) above, please provide details.

Participants will be reimbursed at a rate of 15 £/ hour for participating in the experiment. Each experimental session is expected to take 1.5 h for LBP participants and healthy volunteers

If participants choose to withdraw, how will you deal with compensation?

Participants will be offered compensation based on the time completed (fraction of the total amount based on the time spent at the laboratory).

15. CONFIDENTIALITY

a) Will all participants be anonymous? **Yes** ☒ **No** ☐

b) Will all data be treated as confidential? **Yes** ☒ **No** ☐

Note: Participants' identity/data will be confidential if an assigned ID code or number is used, but it will not be anonymous. Anonymous data cannot be traced back to an individual participant.

Describe the procedures to be used to ensure anonymity of participants and/or confidentiality of data both during the conduct of the research and in the release of its findings.

To reach complete anonymity of the participants, a table will be created to assign an identification number to each participant before being enrolled in the study. The participant, if enrolled in the study, will be asked to remember the assigned identification number and use it during the evaluation session as a mean of identification. The table (key list) containing the connection between the participants' names and the identification numbers will be kept in a locked cabinet in the office of the Principal Investigator. It will not be given to a third party, and it will be stored for 10 years in line with University of Birmingham Research Governance guidelines. The key list will never be present in electronic form. In case of experiment interruption or withdrawal by the participant, personal data for participant identification will be deleted.
All the data collected during the experiment will be strictly confidential, and will not be disclosed to a third party other than the participant and the Principal Investigator. All data will be collected and stored under the identification number allocated at the recruitment.

If participant anonymity or confidentiality is not appropriate to this research project, explain, providing details of how all participants will be advised of the fact that data will not be anonymous or confidential.

16. STORAGE, ACCESS AND DISPOSAL OF DATA

Describe what research data will be stored, where, for what period of time, the measures that will be put in place to ensure security of the data, who will have access to the data, and the method and timing of disposal of the data.

All data from the experiment will be stored in electronic form. The access to the data will be secured through the use of access password and in any case all the acquired data will be anonymous to fully protect the privacy of the participating subjects.
Only PI (Prof. Deborah Falla (DF)) and study supervisors (Dr. Alessandro Marco De Nunzio, Dr. Alison Rushton, Dr. Nicola Heneghan) will be granted with the access to the data. Copy of the encrypted data will be stored on external hard drive and secured in a locked cabinet in the office of the Principal Investigator (DF). It will not be given to a third party, and it will be kept stored for 10 years along with the sheet reporting the access password.
Anonymised data will be submitted for publication, where participants will not be identifiable. The results of the study will be presented at conferences and submitted for publication in scientific journals. Copies of publications can be sent to participants upon their request.

17. OTHER APPROVALS REQUIRED? e.g. Criminal Records Bureau (CRB) checks or NHS R&D approvals.

☐ YES ☒ NO ☐ NOT APPLICABLE

If yes, please specify.

18. SIGNIFICANCE/BENEFITS

Outline the potential significance and/or benefits of the research

There is no immediate benefit to the participants of the study. However the results of this project will increase our understanding of changes in sensory-motor control and muscle synergies behavior in response to LBP. This knowledge is relevant for the development and design of rehabilitation programs for individuals with LBP.

19. RISKS

a) Outline any potential risks to **INDIVIDUALS**, including research staff, research participants, other individuals not involved in the research and the measures that will be taken to minimise any risks and the procedures to be adopted in the event of mishap

We believe that the risk from the procedures proposed within this project is very small.

Non-invasive mounting/attaching procedures of surface electrodes include slight discomfort from minor abrasion of the skin area.

Remote risk of falling:

There could be a remote risk of falling during the postural challenging condition trials as the participants will be asked to lean forward or backward as far as possible. To assure a completely safe environment, an experimenter will stand close to the participant during the entire duration of the tests.
This procedure will prevent any possible fall, which in any case would be very unlikely.

It will be emphasized that participants are free to withdraw at any stage of the study.

Induced anxiety, stress or pain:

Because of their simplicity, motor tasks accomplished by the participants will not lead to anxiety or stress higher than that already expected from everyday life. Scheduled resting periods during the testing sessions will avoid prompting pain or muscular fatigue.

Exacerbation of participant's low back pain:

The participants will be asked to execute simple motor tasks which are usually carried out during a normal daily routine (e.g. standing, walking) and there is a remote risk of little exacerbation of low back pain which will be mitigated just allowing longer resting time and, in the unlikely case that this will not be sufficient and the patient feels uncomfortable , the study session will be immediately stopped and the participant will be disengaged from the study.

Risks induced by pressure and thermal pain threshold test:

The process of evaluating pressure or thermal pain threshold is completely safe, and these tests are commonly applied on people with LBP to elucidate the peripheral and central processing mechanisms that underlie changes in pain sensitivity (Blumenstiel et al., 2011; Hubscher, Moloney, Rebbeck, Traeger, & Refshauge, 2014; O'Neill, Kjaer, Graven-Nielsen, Manniche, & Arendt-Nielsen, 2011).
There is a remote risk for the participants with LBP to have a further pain sensitization undergoing the thermal and pressure pain threshold evaluation. In the unlikely event of a sensitization and persistent increase of LBP the session will be immediately stopped, and the participant will be disengaged from the study.

Moreover, there is no risk of skin bruising or burning induced by the thermal pain threshold test as the device used (Thermal Sensory Analyzer II, Medoc) features safety standards which prevent from any damage to the skin. The device has a temperature limit of 45 C°, and an analog circuit which overrides the system and lowers the temperature gradually as soon as this limit has been reached.

b) Outline any potential risks to **THE ENVIRONMENT and/or SOCIETY** and the measures that will be taken to minimise any risks and the procedures to be adopted in the event of mishap.

No risks to the environment and/or society can be identified in this study.

20. ARE THERE ANY OTHER ETHICAL ISSUES RAISED BY THE RESEARCH?

Yes ☐ **No** ☒

If yes, please specify

21. EXPERT REVIEWER/OPINION

You may be asked to nominate an expert reviewer for certain types of project, including those of an interventional nature or those involving significant risks. If you anticipate that this may apply to your work and you would like to nominate an expert reviewer at this stage, please provide details below.

Contact details (including email address)
Brief explanation of reasons for nominating and/or nominee's suitability

22. CHECKLIST

Please mark if the study involves any of the following:

- Vulnerable groups, such as children and young people aged under 18 years, those with learning disability, or cognitive impairments ☐
- Research that induces or results in or causes anxiety, stress, **pain** or physical discomfort, or poses a risk of harm to participants (which is more than is expected from everyday life) ☒
- Risk to the personal safety of the researcher ☐
- Deception or research that is conducted without full and informed consent of the participants at time study is carried out ☐
- Administration of a chemical agent or vaccines or other substances (including vitamins or food substances) to human participants. ☐
- Production and/or use of genetically modified plants or microbes ☐
- Results that may have an adverse impact on the environment or food safety ☐
- Results that may be used to develop chemical or biological weapons ☐

Please check that the following documents are attached to your application.

	ATTACHED	NOT APPLICABLE
Recruitment advertisement	☒	☐
Participant information sheet	☒	☐
Consent form	☒	☐
Questionnaire	☐	☒
Interview Schedule	☐	☒

23. DECLARATION BY APPLICANTS

I submit this application on the basis that the information it contains is confidential and will be used by the University of Birmingham for the purposes of ethical review and monitoring of the research project described herein, and to satisfy reporting requirements to regulatory bodies. The information will not be used for any other purpose without my prior consent.

I declare that:

- The information in this form together with any accompanying information is complete and correct to the best of my knowledge and belief and I take full responsibility for it.
- I undertake to abide by University Code of Practice for Research (http://www.as.bham.ac.uk/legislation/docs/COP_Research.pdf) alongside any other relevant professional bodies' codes of conduct and/or ethical guidelines.
- I will report any changes affecting the ethical aspects of the project to the University of Birmingham Research Ethics Officer.
- I will report any adverse or unforeseen events which occur to the relevant Ethics Committee via the University of Birmingham Research Ethics Officer.

Name of principal investigator/project supervisor:	
Date:	

Please now save your completed form, print a copy for your records, and then email a copy to the Research Ethics Officer, at aer-ethics@contacts.bham.ac.uk. As noted above, please do not submit a paper copy.

UNIVERSITY OF BIRMINGHAM
APPLICATION FOR ETHICAL REVIEW – REQUEST FOR AMENDMENTS

Who should use this form:

- This form is to be completed by PIs or supervisors (for PGR student research) who are requesting ethical approval for amendments to research projects that have previously received ethical approval from the University of Birmingham.

  Please be aware that all new research projects undertaken by postgraduate research (PGR) students first registered as from 1st September 2008 will be subject to the University's Ethical Review Process. PGR students first registered before 1st September 2008 should refer to their Department/School/College for further advice.

- What constitutes an amendment?

  Amendments requiring approval may include, but are not limited to, additions to the research protocol, study population, recruitment of participants, access to personal records, research instruments, or participant information and consent documentation. Amendments must be approved before they are implemented.

NOTES:

- Answers to questions must be entered in the space provided
- An electronic version of the completed form should be submitted to the Research Ethics Officer, at the following email address: aer-ethics@contacts.bham.ac.uk. Please **do not** submit paper copies.
- If, in any section, you find that you have insufficient space, or you wish to supply additional material not specifically requested by the form, please submit it in a separate file, clearly marked and attached to the submission email.
- If you have any queries about the form, please address them to the Research Ethics Team.

UNIVERSITY OF BIRMINGHAM
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- Answers to questions must be entered in the space provided
- An electronic version of the completed form should be submitted to the Research Ethics Officer, at the following email address: aer-ethics@contacts.bham.ac.uk. Please **do not** submit paper copies.
- If, in any section, you find that you have insufficient space, or you wish to supply additional material not specifically requested by the form, please submit it in a separate file, clearly marked and attached to the submission email.
- If you have any queries about the form, please address them to the Research Ethics Team.

UNIVERSITY OF BIRMINGHAM APPLICATION FOR ETHICAL REVIEW - REQUEST FOR AMENDMENTS	*OFFICE USE ONLY:* Application No: Date Received:

1. **TITLE OF PROJECT**

Influences of low back pain on sensory integration and motor control during activities of daily living

2. **APPROVAL DETAILS**

What is the Ethical Review Number (ERN) for the project?

ERN_16-1389

3. **THIS PROJECT IS:**

University of Birmingham Staff Research project ☒

University of Birmingham Postgraduate Research (PGR) student project ☒

Other ☐(Please specify): Please specify):

4. **INVESTIGATORS**

d) PLEASE GIVE DETAILS OF THE PRINCIPAL INVESTIGATORS OR SUPERVISORS (FOR PGR STUDENT PROJECTS)

Name: Title / first name / family name	Professor Deborah Falla
Highest qualification & position held:	Chair in Rehabilitation Science and Physiotherapy
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

Name: Title / first name / family name	Dr. Alessandro Marco De Nunzio
Highest qualification & position held:	Research Fellow
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

Name: Title / first name / family name	Dr. Alison Rushton
Highest qualification & position held:	Senior Lecturer
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

Name: Title / first name / family name	Dr. Nicola Heneghan
Highest qualification & position held:	Lecturer
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

e) PLEASE GIVE DETAILS OF ANY CO-INVESTIGATORS OR CO-SUPERVISORS (FOR PGR STUDENT PROJECTS)

Name: Title / first name / family name	Nicola Middlebrook
Highest qualification & position held:	MRes student
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

Name: Title / first name / family name	Eduardo Martinez Valdes
Highest qualification & position held:	Research Associate
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

f) In the case of PGR student projects, please give details of the student

Name of student:	Andrew Sanderson	Student No:
Course of study:	PhD	Email
Principal supervisor:	Deborah Falla	

Name of student:	Pauline Kuithan	Student No:
Course of study:	PhD	Email
Principal supervisor:	Deborah Falla	

5. **ESTIMATED START OF PROJECT** Date: 01/04/2017

ESTIMATED END OF PROJECT Date: 31/12/2019

6. **ORIGINAL APPLICATION FOR ETHICAL REVIEW AND ANY SUBSEQUENT APPROVED AMENDMENTS:**

Please complete the table below for the original application and any subsequent amendments submitted

Title and reference number of application or amendment	**Key points of application and/or changes made by amendment (include: aims of study, participant details, how participants were recruited and methodology)**	**Ethical considerations arising from these key points (e.g. gaining consent, risks to participants and/or researcher, points raised by Ethical Review Committee during review)**	**How were the ethical considerations addressed? (e.g. consent form, participant information, adhering to relevant procedures/clearance required)**
Original application Influences of low back pain on sensory integration and motor control during activities of daily living	**Aims**: To understand how the brain orchestrates sensory-motor integration and motor control to manage pain by studying the association between changes in motor control abilities and different pain domains. **Participants**: Healthy subjects will be recruited via poster advertisement at the: - School of Sport, Exercise and Rehabilitation Sciences, College of Life and Environmental Sciences of the University of Birmingham LBP participants will be recruited, via poster advertisement, from the community and population of staff and students at the University of Birmingham. Control participants will be age and gender matched to the LBP participants. **Methods**: Biomechanics of body segments (kinematic and kinetic evaluation), synergistic motor outcome (via high-density electromyography recordings) (EMG) and cortical activity (via electroencephalography) (EEG) will be studied in people with LBP and age-and gender matched control participants. Quantitative sensory tests will be performed including pressure pain thresholds and thermal pain thresholds over regions of the lumbar spine and at a remote site. The project is divided into three separate studies which focus on different motor tasks **4. Postural control in normal and challenged conditions (voluntary holding of a steady inclined position)** **5. Gait Initiation and Sudden Unplanned Gait Termination** **6. Walking along curvilinear path and turning strategies**	**Consent**: Prior to beginning any part of the experiment, it is important that participants will be fully informed of what is expected of them during the experiment. **Risks**: Remote risk of falling; induced anxiety, stress or pain; exacerbation of participant's LBP; risks induced by pressure and thermal pain threshold test **Committee Points**: More information required on the methods and equipment used in the quantitative sensory testing. Clarification required for withdrawal deadline, anonymity and exclusion criteria clarified to participants.	**Consent**: All information regarding the experiment will be provided in the 'Participant Information Leaflet' which will include a description of the study, inclusion and exclusion criteria, risk and benefits. Written informed consent will be obtained after the study has been explained and the volunteers have the opportunity to ask any questions they may have. It will be emphasized that participants are free to withdraw at any stage of the study. **Risks**: *Remote risk of falling*; To assure a completely safe environment, an experimenter will stand close to the participant during the entire duration of the tests. *Induced anxiety, stress or pain*; motor tasks accomplished by the participants will not lead to anxiety or stress higher than that already expected from everyday life. Scheduled resting periods during the testing sessions will avoid prompting pain or muscular fatigue. *Exacerbation of participant's LBP*; motor tasks will replicate those which are usually carried out during a normal daily routine. Any exacerbation will lead to a longer rest time and if necessary the participant will be disengaged from the study. *Risks induced by pressure and thermal pain threshold test;* The process of evaluating pressure or thermal pain threshold is completely safe, and these tests are commonly applied on people with LBP. The device used features safety standards which prevent from any damage to the skin **Committee Points**: All committee points were addressed in the final draft of the approved study, as shown above. In addition, a withdrawal deadline of one month following the experiment was clarified and a new system to obtain anonymity was created.

7. **DETAILS OF PROPOSED <u>NEW AMENDMENT</u>**
Provide details of the proposed new amendment, and clearly and explicitly state how the proposed new amendment will differ from the details of the study as already approved (see Q6 above).

We are requesting two new amendments:
1. Adding a fourth evaluation which investigates a different motor task, and expands on the quantitative sensory testing aspect
2. Amending study recruitment to a] include using social medial as a means of recruitment for this study and b] adjusting recruitment information to accurately reflect the Quantitative sensory tests detailed in the previously approved study.

<u>Amendment 1</u>

SUMMARY OF STUDY 4

4. Muscle behaviour during a dynamic lifting and rotation task and the effect on pain perception and sensitivity

Working Hypotheses

1. It is hypothesised that the pattern of muscle behaviour will be less varied in individuals with low back pain (LBP) than in control participants.
2. It is hypothesised that individuals with LBP will have less range of motion during the repetitive task than those with no pain.
3. It is hypothesised that individuals with LBP will demonstrate altered pain perception and sensitivity to quantitative sensory testing both before and after the repeated lifting task.

<u>Methods</u>

Subjects will be required to stand on a force plate while lifting a weighted box with handles (the weight of the box will be standardised to 5kg to represent a task of daily life) between different levels of shelving in both the sagittal and horizontal plane. Adjustable shelving will be situated around the participant and with the lower shelf at the participant's knee height, level with the lateral epicondyle of the femur, and the higher shelf at shoulder height while standing, level with the acromion. One set of shelving will be anterior to the participant, with further sets lateral to the participant on each side centred on the force plate (**Figure 1**).

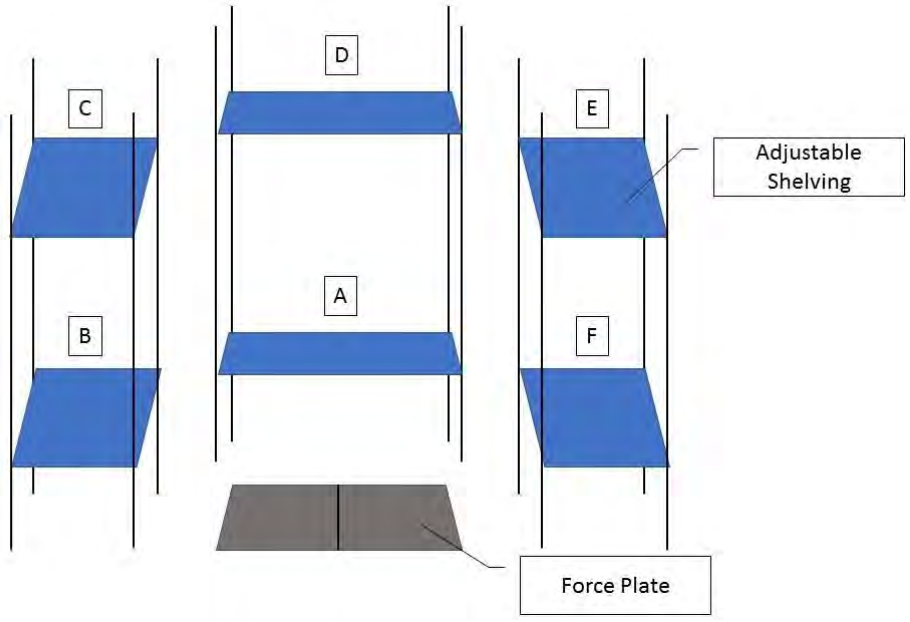


Figure 1 –Experimental set-up with adjustable shelving and a force plate

For the duration of the experimental session, subjects will be instructed to stand barefoot on embedded floor level force plates (BTS Bioengineering, Italy). Participants will be asked to stand with one foot on each force plate with their heels separated by 17cm and at a 14^{o} angle to each other (McIlroy and Maki, 1997). Participants will be asked initially to adopt a 'resting stance' with arms lowered whilst looking at a target placed 40 cm anteriorly.

In line with existing research we will use the following procedure which is adapted slightly from (Falla et al., 2014). At the beginning of the task, the weighted box will be placed on shelf 'A', participants will be instructed to lift the box and move it from A to B, rest for 2 seconds and then return the box to A. This movement task will be repeated for A-C, A-D, A-E and A-F. At this point participants have completed a full cycle of the task and will continue by again moving the box from A-B. In order to allow inter- and intra-participant comparisons, the movements will be timed with an audible metronome as a reference (Falla et al., 2014). Participants will be instructed to complete each movement within two seconds and then will be allowed to rest for two seconds prior to completing the next movement. On this basis, with the maximum of 15 repetitions the entire task will take approximately 10 minutes. Patients will be advised that if the task provokes more discomfort than they would normally experience during activities of daily living, they can stop the task any time, either to rest or stop the task completely. However, a previous comparable study demonstrated no lasting effects beyond some temporary discomfort for some participants (Falla et al., 2014). In addition to this, pilot studies will be used to determine the optimal timing for movements and repetitions to allow for successful completion of the task.

EMG
EMG acquisition and processing will be the same as previously described in the methodology presented for the approved study. The key differences are as follows:

- Arrays of surface electrodes will be used to record EMG from the erector spinae instead of the bipolar EMG previously described
- Bipolar EMG surface electrodes will be used to record EMG signals from additional trunk musculature bilaterally, including the External Oblique (EO) and the Rectus Abdominis (RA)

Kinematics
Movement analysis and processing will be the same as previously described in the methodology presented for studies 2 and 3. The key differences will be as follows:

- The focus of this study is in the movement of the trunk; therefore, the analysed kinematic index will reflect this. The spine will be divided into three triangular segments for analysis of rotation and range of motion (Muller et al., 2016).Thus additional markers will be placed over the spinous processes of S1, T12, T6 and C7 and 10 cm lateral to the spinous processes of T12, T6 and C7.

Data will be acquired in a single session for all participants lasting approximately 2 hours per participant.

Quantitative sensory testing
Pain pressure threshold with an Algometer, thermal pain threshold testing with a thermal stimulator and detection of vibration using a vibrameter over multiple sites of the lower back, within lumbar dermatomes and over a remote side (hand) will be tested before the task referring to standardised protocols (Rolke et al., 2006, O' Conaire et al., 2011, Falla et al., 2014). Pain threshold measurements and detection of vibration will be repeated immediately following the lifting task.

Amendment 2

Amending study recruitment to a] include using social medial as a means of recruitment for this study and b] adjusting recruitment information to accurately reflect the Quantitative sensory tests detailed in the previously approved study.

a] Recruitment will be conducted, as previously stated in the approved study, through poster recruitment at the University of Birmingham.
This will now include posters being displayed both in the physical space within the University of Birmingham and through associated accounts on social media websites. This recruitment information will be posted passively (not as paid-for adverts) on social media websites including Facebook and Twitter. These posts will be visible to anybody who views or subscribes to the accounts but will not be posted excessively or onto a page or group where it is not appropriate.

b] These posters have also been amended slightly to include information relating to the quantitative sensory testing.

8. **JUSTIFICATION FOR PROPOSED NEW AMENDMENT**

Amendment 1

This new amendment will allow the addition a new investigation to the experimental procedure which represents a lifting task which broadly reflects a functional activity of daily living.

Muscle behaviour is known to be altered with fatigue and pain (Hodson-Tole and Wakeling, 2009, Tucker et al., 2009). Recent advances in high density electromyography (HDEMG), has allowed researches to investigate muscle behaviour in a more comprehensive manner (Martinez-Valdes et al., 2016, Falla et al., 2014). Using this technique, it has also been shown that there are significant differences in the activation of the lumbar erector spinae in participants with LBP during a repeated dynamic movement when compared to pain free participants (Falla et al., 2014). In this previous experiment it was shown that the activation of this muscle in individuals with LBP remained stationary during movement, while in pain free participants the distribution of activity changed and this difference in muscle behaviour was also associated with greater muscle fatigue for the patient group. However, this study only assessed the lumbar erector spinae unilaterally during a task which included only sagittal movement (Falla et al., 2014).

Previous studies have shown that there is also a link between the rotation of the trunk and LBP. This link includes a decreased range of motion during rotation in the both pelvic and lumbar region in patients with LBP (Sung, 2014, Shojaei et al., 2017a, Shojaei et al., 2017b). Furthermore it was also found that manual labourers who lift loads whilst undergoing trunk rotation were more likely to develop LBP (Hoogendoorn et al., 2000). Yet currently no studies have evaluated the distribution of erector spinae muscle activity during repeated rotational movements in people with LBP. Such knowledge will allow for a deeper understanding of how a dynamic movement is completed in individuals with and without LBP and inform future research.

To investigate the second working hypothesis, it is necessary to complete a kinematic analysis of the movement required to investigate the first working hypothesis. This kinematic analysis is important because the participants will not be forced to conform in their movement strategy; instead a suggested movement will be demonstrated prior to commencement of the experiment. It is expected that while most participants will copy the demonstrated strategy initially; individuals who have LBP may utilise adaptive movement strategies as has been demonstrated in previous studies (Basques et al., 2016, Falla et al., 2014, Koes et al., 2006, van Tulder and Koes, 2006).

Regarding the third hypothesis, research provided evidence that at least some patients with low back pain present altered pain thresholds, decreased endogenous pain inhibition as well as facilitated temporal summation (Nijs et al., 2015, Falla et al., 2014, Rabey et al., 2015, Vaegter and Graven-Nielsen, 2016, Roussel et al., 2013). However, the changes in pain thresholds and mechanical detection after repeated movements has not been well investigated in LBP. Such knowledge could inform the establishment of subgroups for pain-mechanism based treatment approaches.

Amendment 2

This new means of disseminating the recruitment material is intended to better reflect the daily habits of potential participants. It has previously been shown that recruitment though social media is an effective means of reaching and recruiting more participants over a short period of time (Khatri et al., 2015). This means of advertising will also allow for the recruitment of a sample which is more representative of the population, as it is not limited to individuals who visit the University of Birmingham campus. The recruitment information which will be displayed through social media will not differ from that displayed on the physical campus.
The slight amendments to the content of the recruitment posters has enabled accurate presentation of the study.

9. **ETHICAL CONSIDERATIONS**

What ethical considerations, if any, are raised by the proposed new amendment?

The task may contribute to a temporary exacerbation of a participant's LBP consistent with how their pain may be exacerbated through normal physical activity.

The trunk rotation and lifting task presented has been designed to reflect normal function and is not expected to cause symptoms beyond those that participants may experience during routine activities of daily living or physical exercise. Participants will however be advised to immediately stop the task and rest until they feel able to continue and they will also have the option to stop and withdraw from the study at any time. Participants will be monitored carefully for symptom reproduction by the research team which includes experienced clinicians and researchers.

10. **DECLARATION BY APPLICANTS**

I make this application on the basis that the information it contains is confidential and will be used by the University of Birmingham for the purposes of ethical review and monitoring of the research project described herein, and to satisfy reporting requirements to regulatory bodies. The information will not be used for any other purpose without my prior consent.

I declare that:

- The information in this form together with any accompanying information is complete and correct to the best of my knowledge and belief and I take full responsibility for it.
- I undertake to abide by University Code of Conduct for Research (http://www.birmingham.ac.uk/Documents/university/legal/research.pdf) alongside any other relevant professional bodies' codes of conduct and/or ethical guidelines.
- I will report any changes affecting the ethical aspects of the project to the University of Birmingham Research Ethics Officer.
- I will report any adverse or unforeseen events which occur to the relevant Ethics Committee project to the University of Birmingham Research Ethics Officer.

Signature of Principal investigator/project supervisor:	
Date:	12/04/17

Andrew Sanderson (PhD School of Sprt+Ex Scie FT)

From: Pauline Kuithan
Sent: 17 August 2017 12:14
To: Andrew Sanderson (PhD School of Sprt+Ex Scie FT)
Subject: FW: Application for amendment ERN_16-1389B

From: Samantha Waldron
Sent: 15 August 2017 08:39
To: Deborah Falla; Nicola Heneghan; Alessandro De Nunzio; Alison Rushton
Cc: Pauline Kuithan
Subject: Application for amendment ERN_16-1389B

Dear Professor Deborah Falla, Dr. Alessandro Marco De Nunzio, Dr. Alison Rushton& Dr. Nicola Heneghan

Re: "Influences of low back pain on sensory integration and motor control during activities of daily living"
Application for amendment ERN_16-1389B

Thank you for the above application for amendment, which was reviewed by the Science, Technology, Engineering and Mathematics Ethical Review Committee.

On behalf of the Committee, I can confirm that this amendment now has full ethical approval.

I would like to remind you that any substantive changes to the nature of the study as now amended, and/or any adverse events occurring during the study should be promptly bought to the Committee's attention by the Principal Investigator and may necessitate further ethical review. A revised amendment application form is now available at https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research-Ethics/Ethical-Review-Forms.aspx . Please ensure this form is submitted for any further amendments.

Please also ensure that the relevant requirements within the University's Code of Practice for Research and the information and guidance provided on the University's ethics webpages (available at https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research-Ethics/Links-and-Resources.aspx) are adhered to and referred to in any future applications for ethical review. It is now a requirement on the revised application form (https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research-Ethics/Ethical-Review-Forms.aspx) to confirm that this guidance has been consulted and is understood, and that it has been taken into account when completing your application for ethical review.

Please be aware that whilst Health and Safety (H&S) issues may be considered during the ethical review process, you are still required to follow the University's guidance on H&S and to ensure that H&S risk assessments have been carried out as appropriate. For further information about this, please contact your School H&S representative or the University's H&S Unit at healthandsafety@contacts.bham.ac.uk.

If you require a hard copy of this correspondence, please let me know.

Kind regards,

The University of Birmingham

School of Sport, Exercise and Rehabilitation Sciences

Participant Information Leaflet

Study title

Influences of Low Back Pain on Sensory Integration and Motor Control during activities of daily living

1. Invitation

You are being invited to take part in a research study. Before you decide to participate it is important you understand why the research is being done and what it will involve. Please take time to read the following information sheet carefully and discuss it with the researcher or others if you wish.

2. What is the purpose of the study?

Low back pain (LBP) is a major clinical problem with substantial socio-economic impact. Current diagnosis and therapy are insufficient, and knowledge concerning the interaction between musculoskeletal pain and movement is incomplete. Therefore, the aim of this study is to investigate how sensations, e.g. vision, touch, are used by the brain to manage and control the execution of activities of daily living in presence of LBP.

3. Why have I been chosen?

You have been chosen because we understand you have previously experienced a back pain problem that has the following characteristics:

- It has lasted more than 3 months,
- You have experienced pain on more than 90 days out of the past 6 months Other inclusion criteria include:
- Aged between 18 and 65 years

While exclusion criteria include:

- Concurrent systemic, rheumatic or neuro-musculoskeletal disorders which may confound testing or if you are currently pregnant.
- Radiating leg pain, or low back pain related to trauma, fractures, spinal stenosis.
- Higher doses of pain killers (> 30 mg of morphine equivalent dose)
- Being under active management of LBP through specific medications prescribed by a GP or receiving therapies e.g. physiotherapy.

4. Do I have to take part?

You are free to decide whether you participate or not. If you agree to take part you are free to withdraw at any time during the experimental session and you can withdraw your data up to 1 month following data collection without giving a reason. Any decision to withdraw will not in any way affect any future care with the health service. If you withdraw from the study all the data acquired will be destroyed immediately.

5. What do I have to do?

You will be asked to visit the Human Movement Laboratory in the School of Sport, Exercise and Rehabilitation Sciences for approximately 2-3 hours. During this time you will be asked to do the following

- Complete a brief questionnaire where eligibility will be confirmed.
- Complete some clinical measures to rate and evaluate your LBP condition. Among these clinical measures, a pressure pain threshold, a thermal pain threshold test, and a test for the sense of vibration are included. The pressure pain threshold test is executed using a hand-held probe pushed on the skin at a constant pressure (CE marked device). You have to indicate when pain is perceived for the first time. The thermal threshold test is executed using a heating probe placed on the skin (CE marked device) on the same spot previously used for the pressure threshold test. You have to indicate when pain is perceived for the first time during the thermal stimulation. In addition to it, we use thermal stimuli to provoke a serious of minor painful stimuli to investigate the change of pain levels you perceive. You can stop the test at any time.

- Perform a range of simple tasks to measure your movement control e.g. lifting a small weight between shelves in a cyclical pattern, and walking in a circular motion.

6. Will my taking part in this study be kept confidential?

All information collected on you will be kept strictly confidential. Personal information will be retained, but only available to the researchers using password protected files. All data for presentation will be anonymised, so your identity will not be revealed in any way.

7. What will happen to the results of the research study?

The findings from this study will be presented, or shared with other researchers in the form of presentations and scientific papers as appropriate. These will be used to help inform about new possible findings regarding LBP, its evolution and effect on movement control during daily activities.

8. Does the study follow Ethics prescriptions?

This study, as all the research involving human subjects, underwent the ethical review processes of the University of Birmingham and received official approval from the University Ethics Committee.

9. Who is organising and funding the research?

The study has been designed and organised by Prof. Deborah Falla, Dr. Alessandro De Nunzio, Dr. Nicola Heneghan and Dr. Alison Rushton and supported by PhD students from the School of Sport, Exercise and Rehabilitation Sciences. As a participant, you will receive a reimbursement of £15. In case of early withdrawal you will be offered compensation based on the time completed (fraction of the total amount based on the time spent at the laboratory).

Contact details for further information, please contact Andy Sanderson

Project Supervisor Prof. Deborah Falla Chair in Rehabilitation Science and Physiotherapy School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
Project co-investigator Dr. Alessandro M. De Nunzio Senior Research Fellow School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
Project co-investigator Dr. Alison Rushton Senior Lecturer School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
Project co-investigator Dr. Nicola Heneghan Lecturer School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
PhD Student **Andy Sanderson** **School of Sport, Exercise and Rehabilitation Sciences** **University of Birmingham**	
PhD Student Pauline Kuithan School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	

Thank you for taking time to read this and considering taking part in the study.

The University of Birmingham

School of Sport, Exercise and Rehabilitation Sciences Participant Information Leaflet

Study title

Influences of Low Back Pain on Sensory Integration and Motor Control during activities of daily living

1. Invitation

You are being invited to take part in a research study. Before you decide to participate it is important you understand why the research is being done and what it will involve. Please take time to read the following information sheet carefully and discuss it with the researcher or others if you wish.

2. What is the purpose of the study?

Low back pain (LBP) is a major clinical problem with substantial socio-economic impact. Current diagnosis and therapy are insufficient, and knowledge concerning the interaction between musculoskeletal pain and motor performance is incomplete. Therefore, the aim of this study is to investigate how sensory information is used by the brain to manage and control the execution of activities of daily living in presence of LBP.

3. Why have I been chosen?

You have been chosen because we understand that you, as healthy and physically active subject could represent a control in this study.
Inclusion criteria include:

- Aged between 18 and 65 years

While exclusion criteria include:

- Current or previous history of back or lower limb pain
- Neuromuscular disorders - Musculoskeletal impairment.

4. Do I have to take part?

You are free to decide whether you participate or not. If you agree to take part you are free to withdraw at any time during the experimental session and you can withdraw your data for up to 1 month following data collection without giving a reason. Any decision to withdraw will not in any way affect any future care with the health service. If you withdraw from the study all the data acquired will be destroyed immediately.

5. What do I have to do?

You will be asked to visit the Human Movement Laboratory in the School of Sport, Exercise and Rehabilitation Sciences for approximately 120 minutes. During this time you will be asked to do the following

- Complete a brief questionnaire where eligibility will be confirmed.
- Complete some clinical measures to rate your skin sensitivity. Among these clinical measures, a pressure pain threshold,a thermal pain threshold test, and a test for the sense of vibration are included. The pressure pain threshold test is executed using a hand-held probe pushed on the skin at a constant pressure (CE marked device). You have to indicate when pain is perceived for the first time. The thermal threshold test is executed using a heating probe placed on the skin (CE marked device) on the same spot previously used for the pressure threshold test. You have to indicate when pain is perceived for the first time during the thermal stimulation. In addition to it, we use thermal stimuli to provoke a serious of minor painful stimuli to investigate the change of pain levels you perceive. You can stop the test at any time.
- Perform a range of simple tasks to measure your movement control e.g. lifting a small weight between shelves in a cyclical pattern, and walking in a circular motion.

6. Will my taking part in this study be kept confidential?

All information collected on you will be kept strictly confidential. Personal information will be retained, but only available to the researchers using password protected files. All data for presentation will be anonymised and aggregated, so your identity will not be revealed in any way.

7. What will happen to the results of the research study?

The findings from this study will be presented, or shared with other researchers in the form of presentations and scientific papers as appropriate. These will be used to help inform about new possible findings regarding LBP, its evolution and effect on motor control during ADL.

8. Does the study follow Ethics prescriptions?

This study, as all the research involving human subjects, underwent the ethical review processes of the University of Birmingham and received official approval from the University Ethics Committee

9. Who is organising and funding the research?

The study has been designed and organised by Prof. Deborah Falla, Dr. Alessandro De Nunzio, Dr. Nicola Heneghan and Dr. Alison Rushton and supported by PhD students from the School of Sport, Exercise and Rehabilitation Sciences. As a participant, you will receive a reimbursement of £15. In case of withdraw you will be offered compensation based on the time completed (fraction of the total amount based on the time spent at the laboratory).

Contact details for further information, please contact Andy Sanderson

Project Supervisor Prof. Deborah Falla Chair in Rehabilitation Science and Physiotherapy School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
Project co-investigator Dr. Alessandro M. De Nunzio Senior Research Fellow School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
Project co-investigator Dr. Alison Rushton Senior Lecturer School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
Project co-investigator Dr. Nicola Heneghan Lecturer School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
PhD Student **Andy Sanderson** **School of Sport, Exercise and Rehabilitation Sciences** **University of Birmingham**	
PhD Student Pauline Kuithan School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	

Thank you for taking time to read this and considering taking part in the study.

Consent Form

Study ID:

Influences of Low Back Pain on Sensory Integration and Motor Control during activities of daily living

This information is being collected as part of a research project concerned with the investigation of sensory-motor integration processes and its changes to manage chronic LBP during the execution of activities of daily living (ADL) tasks, by the School of Sport, Exercise and Rehabilitation Sciences at the University of Birmingham. The information which you supply and that which may be collected as part of the research project will be entered into a filing system or database and will only be accessed by authorised personnel involved in the project. The information will be retained by the University of Birmingham and will only be used for the purpose of research and statistical and audit purposes. By supplying this information you are consenting to the University storing your information for the purposes stated above. The information will be processed by the University of Birmingham in accordance with the provisions of the Data Protection Act 1998. No identifiable personal data will be published.

- I confirm that I have read and understand the participant information leaflet for this study. I have had the opportunity to ask questions if necessary and have had these answered satisfactorily.
- I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason as I will have the right to withdraw my data from the study up to 1 month following data collection. If I withdraw my data will be removed from the study and will be destroyed. Participants will be free to withdraw at any time during the experimental session and.
- I understand that my personal data will be processed for the purposes detailed above, in accordance with the Data Protection Act 1998.
- Based upon the above, I agree to take part in this study.

Name of participant…… Date…… Signature……..

Name of researcher/ individual obtaining consent…… Date…… Signature……..

<u>Contact details of participant</u>

Contact number:

Email address:

Appendix 10 – Custom Low Back Pain Questionnaire

Andy Sanderson & Pauline Kuithan

Study ID:

Profession: _____ employed □ unemployed □ student □

Highest level of education attained: _____ Ethnicity: _____

Date of Birth: Gender: m □ f□ currently pregnant □

Height: Weight: BMI: (Calculated by us)

Sternum Height: Knee Height: Distance between elbows:

Arm length:

Have you ever experienced low back pain in your life? **Yes** □ **No** □

1. Within the **last three years** have you had **low back pain** or **lower limb pain or injury** that has limited function and/or **required treatment** from a health profession?
   No □ Yes □ _____
2. Have you been diagnosed with
   - radicular low back pain **Yes** □ **No** □
   - pain related to trauma, fractures or spinal stenosis **Yes** □ **No** □
   - concurrent systemic, rheumatic or neuro-musculoskeletal disorders **Yes** □ **No** □
3. Have you taken specific medications prescribed by a GP, consultant or therapists or higher doses of opioids (> 30 mg of morphine equivalent dose) within the last three months? **Yes** □ **No** □
4. Are you currently seeking treatment/ under active management? **Yes** □ **No** □

Back pain

5. Has your pain persisted at least 3 months and resulted in pain on at least half the days in the past 6 months? (if no skip the following questions) **Yes** □ **No** □
6. When was your first episode of back pain? What caused it?
   Year: cause: _____
7. How often do you get episodes of low back pain?
   Constant pain □ almost constant pain □ _____ year _____months
8. How long does your back pain usually last for if not constant?
   _____ years _____ months_____ weeks _____ days
9. Have you ever experienced any of those features with your back pain?
   numbness □ weakness □ pins and needles □ burning □ leg pain □

Most recent episode

10. When did this episode start?
    ____ years ____ months ____ weeks ____ days
11. How would you rate the average intensity of your most recent episode of back pain?
    Please rate your pain levels from 0 'no pain' and 10 'pain as bad as it could be'

0 1 2 3 4 5 6 7 8 9 10

Current back pain

12. What best describes your current low back pain state within the last 4 weeks?
    stable □ getting better □ getting worse □
    fluctuant with pain free episodes □ fluctuant without pain free episodes □
13. How would you describe your pain (most painful area)?
    _____
14. Which activities provoke your pain?
    _____
15. If an activity provokes your pain, how long does it last for?
    ____ days ____ hours ____ minutes ____ seconds
16. If you think of the following activities, do you think they could increase your back pain?
    Bending □ Trunk Rotation □ Sitting □ Standing □ Standing Up □ Lifting □
    Sitting Down □ Carrying □ Picking Something Up □ Overhead Activity □
17. Which activities or techniques do you use to alleviate your pain?
    _____
18. Have you taken any pain medication within the last 24 hours? Please specify if so.
    No □ **Yes** □ _____

Please rate your pain levels from 0 'no pain' and 10 'pain as bad as it could be'

19. How would you rate your back pain right now?

0 1 2 3 4 5 6 7 8 9 10

20. How would you rate the average intensity of your back pain during the last 24 hours?

0 1 2 3 4 5 6 7 8 9 10

21. In the previous four weeks, how intense was your worst pain?

0 1 2 3 4 5 6 7 8 9 10

Treatment history

In the past, did you ever receive any of the following treatments and if so, did they contribute to your health?

	no	Yes, with success	Yes, with temporary success	Yes, but no improvement
Pain medication				
Physiotherapy				
Advice on bending				
Advice on lifting				

Thank you very much!

Appendix 11 – Ethical Review, Consent Forms and Patient Information Sheets for Chapter Six

UNIVERSITY OF BIRMINGHAM
APPLICATION FOR ETHICAL REVIEW

Who should use this form:

This form is to be completed by PIs or supervisors (for PGR student research) who have completed the University of Birmingham's Ethical Review of Research Self Assessment Form (SAF) and have decided that further ethical review and approval is required before the commencement of a given Research Project.

Please be aware that all new research projects undertaken by postgraduate research (PGR) students first registered as from 1st September 2008 will be subject to the University's Ethical Review Process. PGR students first registered before 1st September 2008 should refer to their Department/School/College for further advice.

Researchers in the following categories are to use this form:

1. The project is to be conducted by:
   - staff of the University of Birmingham; or
   - postgraduate research (PGR) students enrolled at the University of Birmingham (to be completed by the student's supervisor);
2. The project is to be conducted at the University of Birmingham by visiting researchers.

Students undertaking undergraduate projects and taught postgraduate (PGT) students should refer to their Department/School for advice.

NOTES:

- An electronic version of the completed form should be submitted to the Research Ethics Officer, at the following email address: aer-ethics@contacts.bham.ac.uk. Please **do not** submit paper copies.
- If, in any section, you find that you have insufficient space, or you wish to supply additional material not specifically requested by the form, please it in a separate file, clearly marked and attached to the submission email.
- If you have any queries about the form, please address them to the Research Ethics Team.

☒ **Before submitting, please tick this box to confirm that you have consulted and understood the following information and guidance and that you have taken it into account when completing your application:**

- **The information and guidance provided on the University's ethics webpages (https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research-Ethics/Ethical-Review-of-Research.aspx)**
- **The University's Code of Practice for Research (http://www.as.bham.ac.uk/legislation/docs/COP_Research.pdf)**

UNIVERSITY OF BIRMINGHAM APPLICATION FOR ETHICAL REVIEW	*OFFICE USE ONLY:* Application No: Date Received:

1. TITLE OF PROJECT

Can detailed biofeedback on muscle activity enhance subjective and objective markers of performance in people with and without low back pain?

2. THIS PROJECT IS:

University of Birmingham Staff Research project ☐
University of Birmingham Postgraduate Research (PGR) Student project ☒
Other ☐ (Please specify):

3. INVESTIGATORS

a) PLEASE GIVE DETAILS OF THE PRINCIPAL INVESTIGATORS OR SUPERVISORS (FOR PGR STUDENT PROJECTS)

Name: Title / first name / family name	Professor Deborah Falla
Highest qualification & position held:	Chair in Rehabilitation Science and Physiotherapy
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

Name: Title / first name / family name	Dr. Alison Rushton
Highest qualification & position held:	Reader
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

Name: Title / first name / family name	Dr. Nicola Heneghan
Highest qualification & position held:	Lecturer
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

b) PLEASE GIVE DETAILS OF ANY CO-INVESTIGATORS OR CO-SUPERVISORS (FOR PGR STUDENT PROJECTS)

Name: Title / first name / family name	Dr. Eduardo Martinez Valdes
Highest qualification & position held:	Lecturer
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

c) In the case of PGR student projects, please give details of the student

Name of student:	Andy Sanderson	Student No:	
Course of study:	PhD	Email address:	
Principal supervisor:	Prof. Falla		

4. ESTIMATED START OF PROJECT Date: 01/09/18

ESTIMATED END OF PROJECT Date: 31/12/2019

5. FUNDING

List the funding sources (including internal sources) and give the status of each source.

Funding Body	*Approved/Pending /To be submitted*
CPR Spine Internal Funding	Approved

If you are requesting a quick turnaround on your application, please explain the reasons below (including funding-related deadlines). You should be aware that whilst effort will be made in cases of genuine urgency, it will not always be possible for the Ethics Committees to meet such requests.

6. SUMMARY OF PROJECT

Describe the purpose, background rationale for the proposed project, as well as the hypotheses/research questions to be examined and expected outcomes. This description should be in everyday language that is free from jargon. Please explain any technical terms or discipline-specific phrases.

Low back pain (LBP) is a major health issue leading to a considerable loss of quality of life and lost days of work (1). Previous research has shown that LBP can cause altered activation of paraspinal muscles, affecting the individual's ability to complete tasks of daily life (2).

Surface electromyography (EMG) is a non-invasive technique which is commonly used in research and clinical practice to assess muscle activity (3). Bipolar EMG involves the placement of a pair of electrodes on the skin directly overlying a muscle, which allows that one subsection of muscle to be measured. However, this does not provide a full picture of the more complex interactions and strategies within that muscle. More recently, high-density EMG (HDEMG), which allows the sampling of activity across many multiple adjacent muscle sites, has been used to investigate the topographical distribution of activity across a muscle (4).

Previous HDEMG investigations in people with low back pain have revealed significant differences in the spatial distribution of back muscle activity when compared to control participants (5, 6). Notably, when investigating the distribution of activity, many studies have investigated the movement of the centre of activity (centroid) during the task (5-10). Studies have shown that the magnitude of the 'shift' in the centroid is positively associated with time to task failure and fatigue (6, 10). A further study from within the University of Birmingham, which is currently being prepared for publication, has studied this effect in LBP and control participants (ERN_17-0782). In this study, a relationship was found between the magnitude of the shift in the centroid location and the time to task failure in a lumbar endurance task, where individuals exhibiting a greater redistribution of muscle activity were able to sustain the task for longer.

Biofeedback defines a tool whereby a biological response from the body is used as a form of feedback to the individual, giving people the opportunity to control processes which were previously considered involuntary (11). Several studies have used classic EMG biofeedback as a means to modulate muscle activity in people with LBP, showing significant favourable results (13). More recent studies have used HDEMG amplitude biofeedback on the trapezius (14, 15), however these studies have used the HDEMG grid to produce only analogue (yes/no) biofeedback. In this study we intend to use state of the art technology to allow participants to see topographical distributions of their back-muscle activity by acquiring and displaying HDEMG amplitude in real time as colourised maps (example; Fig. 1) and use this tool to allow participants to try to alter the distribution of back muscle activity with the aim of enhancing their motor output (e.g. prolonging their endurance).

This form of feedback is significantly more detailed than those used in previous studies, and as such, we expect that participants may be able to utilise the biofeedback more effectively. By providing the participants specific information on where in their muscles a contraction is taking place, we would expect to see an enhanced effect of the feedback when compared to the less detailed analogue style feedback.

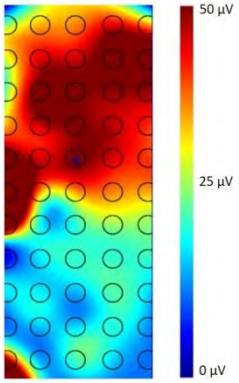


Fig.1 An example biofeedback grid reporting HDEMG amplitude, where red denotes higher muscle activity and blue is lower activity

Objectives

1. **To investigate whether people with LBP can modify the distribution of lumbar Erector Spinae (ES) activity based on detailed feedback from HDEMG.**
2. **To investigate whether detailed HDEMG biofeedback can modify both patient reported outcomes (fatigue, pain) and performance based outcomes (endurance) while completing static and dynamic tasks**

Hypotheses

1. **Participants with LBP will be able to control the activation of their ES by voluntarily shifting the centroid of the HDEMG amplitude map thereby inducing a greater redistribution of activity during both isometric and dynamic tasks**
2. **LBP participants who are able to utilise the HDEMG biofeedback to shift the centroid of the HDEMG amplitude map, thereby inducing a greater redistribution of activity, will show favourable outcomes in terms of pain and fatigue and demonstrate longer endurance**

When completed, the results of this study will form part of a PhD thesis, will be published in a relevant scientific journal and presented at a scientific conference.

7. CONDUCT OF PROJECT

Please give a description of the research methodology that will be used

Study design

Observational cross-sectional study

Participants

A group of 20 participants (men and women aged 18-55) with chronic LBP (non-specific LBP lasting for at least half of the days of the previous 6 months) and a group of 20 age-and gender-matched asymptomatic volunteers will be recruited from the University population and local community. Interested participants will be given a participant information form and screened for study eligibility.

Exclusion criteria for the LBP group includes spinal surgery, spinal fractures, scoliosis major respiratory or neurological conditions, recent or current pregnancies, back pain radiating below the buttock, current treatment for LBP by a health care professional, prescription strength medications such as opioids, anticonvulsives, or regular high-dosed anti-inflammatories.

Exclusion criteria for the control group will include any history of spinal surgery or fractures, major respiratory or neurological conditions, recent or current pregnancies, any pain which radiates down the leg, prescription strength medications such as opioids, anticonvulsives, or regular high-dosed anti-inflammatories. Additionally, participants will be excluded if they have had any LBP in in at least 5 years which has required treatment from a health care practitioner or report any history of low back pain in the last 3 months.

In the instance that participants are uncomfortable participating with just one researcher present for any reason, as the researcher is a male a female member of staff can be requested to be present for the sessions.

Measurement Objectives

The outcomes of this study will reflect the performance measured- and patient reported- outcomes described previously. To facilitate this, and for ease of understanding the methods described next, the outcomes will be measured as follows;

- Patient Reported Outcomes
    - **Pain** – Participants will be asked at 30 s intervals throughout the tasks to rank their pain using the NRS, additionally they will also be asked to rank their pain immediately following the completion of the tasks.
    - **Fatigue** - Participants will be asked at 30 s intervals throughout the tasks to rank their exertion using the Borg Scale, they will also be asked to rank their exertion immediately following the completion of the tasks.
- Performance Measured Outcomes
    - **Endurance** – During the static task, participants will be asked to sustain the position until task failure, the time for which participants could sustain the task will be recorded using a stopwatch.
- EMG and Kinematic Outcomes
    - **EMG** – In order to understand the muscle activation patterns in conditions with and without biofeedback and any changes that occur throughout the contractions will be measured using HDEMG. The outcomes of interest will include the amplitude (RMS), the fatigue (MNF), x and y coordinates of the centroid and the entropy of the signal
    - **Kinematics** – To understand the adaptations of the participants when they use the biofeedback, 3D kinematics will be used to understand how participants move differently in the biofeedback condition compared to no feedback.

Study Protocol

All participants will be assessed in two sessions, taking approximately 2 hours per session with at least 72 hours between sessions, but no longer than one week apart.

Questionnaires – Baseline Characteristics

Participants will be asked to complete the following questionnaires in the first session in order to gain information about the sample, particularly relating to their pain and disability level.

- Custom LBP questionnaire to assess eligibility criteria
- Oswestry Disability Index (ODI) (17)
- Pain Numeric Rating Scale; current and over the preceding week (1-10; PNRS) (18)
- Tampa Scale for Kinesiophobia (TSK) (19)
- International Physical Activity Questionnaire (IPAQ) (20)
- Custom Self-Efficacy scale for utilising the biofeedback (0-100) (21)

Participants will also be asked to complete digital pain drawings on the day of each session, including a drawing of common areas of pain from the previous month, pain on the day of the session prior to the task (23). Moreover, they will also be asked to rate their current pain intensity (PNRS) at the beginning of each session.

HDEMG

In both sessions, activity of the lumbar erector spinae will be measured using wireless 32- channel (8x4) electrode grids (LiSIN, Torino, Italy). The bottom edge of the grid will be placed on a line drawn at the level of the L5 spinous process, with the grid extending cranially. Bipolar EMG (SPES Medica) will be recorded from the abdominal musculature, with electrodes placed bilaterally on the rectus abdominus, the external oblique and the internal oblique.

Prior to the application of the electrodes, the skin will be prepared. This will comprise of marking the area which will be used with a surgical pen, applying an abrasive scrub (NuPrep) to the marked area then cleaning the area with water and drying it. The electrodes will then be applied to the skin. To reinforce the adhesive and prevent movement of the electrodes during the task, hypofix tape (BSN Medical) will be used, which is a tape designed for use on the skin.

The EMG signals will be amplified (Wireless-EMG, 64-channel EMG amplifier, LiSIN, Torino, Italy, 3dB, bandwidth 10-500 Hz) and stored on a laptop hard drive. Following the data collection session, the data will be backed up on the University of Birmingham research data store and processed as follows. The root mean square (RMS) will be calculated from 28 bipolar signals in each grid and EMG data from each repetition will be normalised to data obtained from the first repetition. The centroid of activation will be calculated and the 2D displacement of the centroid defined as the variability in activation.

Additionally, real-time visualisation of the RMS will be displayed in the form of a topographical colour map (Fig. 1). Participants will be familiarised with the orientation of the grids prior to the beginning of the session so that they are able to understand the relationship to their own back. The maps will be displayed to the participants with clear instructions given to encourage redistribution of activity. The maps will be displayed to participants using virtual reality or augmented reality glasses, which can allow the visualisation of a computer screen without the participant needing to turn their head, allowing full freedom of movement.

Kinematics

In order to accurately assess the movement of the participants, kinematic markers will be used to allow for a 3D reconstruction of the participants' movements. The kinematic recording and analysis will be achieved using the BTS Smart DX suite of software (BTS, Milan, Italy).

To achieve this, reflective kinematics markers must be adhered to the skin lying over anatomical landmarks. The markers will be placed over the following positions bilaterally – the base of metacarpal 5; the lateral malleolus; the heel; the lateral epicondyle of the knee; the iliac crest on the mid-axillary line; 10cm lateral to T12 and 10cm lateral to T6. Additionally, these points will be marked unilaterally as they are on the mid-line – the spinous processes of C7, T6, T12 and S1.

This outcome will look for changes in participants' movement patterns when comparing the conditions with and without the biofeedback. This will include differences between groups (LBP vs control), between conditions for groups (LBP Biofeedback vs LBP no feedback) and for individuals (Participant 7 Biofeedback vs Participant 7 No feedback).

Tasks

As with previous studies within the lab, we will assess the activation of the lumbar ES using tasks which represent those of daily life similar to those used previously (Static - ERN_17-0782; Dynamic - ERN_16-1389B). These tasks are designed to fatigue the ES, but not to cause undue or persistent discomfort. Our experience from these previous projects is that any sense of discomfort or fatigue have resolved immediately following completion of the task.

A static contraction will be performed to evaluate endurance. In this instance, the participant will be positioned in prone and will be asked to extend their lumbar spine to raise their trunk, they will then be asked to sustain this position for as long as possible up to a maximum of 5 minutes. By assigning a maximum time for endurance contractions to 5 minutes minimises any aggravation of LBP and injury.

In the other session, the participants will perform a dynamic task involving a repeated movement of lifting a box (5kg mass) between different shelves similar to the task as performed in our previous study (ERN_16-1389B). In order to allow inter- and intra-participant comparisons, the movements would be timed with an audible metronome as a reference (6).

In each session, participants will be asked to complete one static and one dynamic task, in one session participants will be able to utilise the biofeedback tool designed for this study and in the other session participants will complete the task with no feedback. Within the sessions the order of tasks will remain consistent, with the dynamic task always preceding the static task. A 15 minute rest period will be observed between tasks in order to reduce the effects of fatigue. The order of sessions, biofeedback/no-feedback will be randomised using a random number generator prior to the start of session 1.

Participants will be reminded that if the task provokes more discomfort than they would normally experience during activities of daily living, they can and should stop the task any time, either to rest or stop the task completely. However, our previous studies using similar tasks as described here have demonstrated no lasting effects beyond some temporary discomfort for some participants which quickly diminished when the task was completed.

Throughout the tasks, participants will be asked to report their rate of perceived exertion at 30s intervals. This is a measure of suitability to ensure that LBP and control participants find the task equally difficult (24). Additionally, to better understand the progression of pain throughout the task the participants will be asked to rank their pain out of 10 at 30s intervals during the task and following completion of the task.

8. DOES THE PROJECT INVOLVE PARTICIPATION OF PEOPLE OTHER THAN THE RESEARCHERS AND SUPERVISORS?

Yes ☒ No ☐

Note: 'Participation' includes both active participation (such as when participants take part in an interview) and cases where participants take part in the study without their knowledge and consent at the time (for example, in crowd behaviour research).

If you have answered NO please go to Section 18. If you have answered YES to this question please complete all the following sections.

9. PARTICIPANTS AS THE SUBJECTS OF THE RESEARCH

Describe the number of participants and important characteristics (such as age, gender, location, affiliation, level of fitness, intellectual ability etc.). Specify any inclusion/exclusion criteria to be used.

A group of 20 participants (men and women aged 18-55) with chronic LBP (non-specific LBP present for half of the days of the previous 6 months) and a group of 20 age-and gender-matched asymptomatic volunteers (no relevant history of LBP in at least 5 years and no LBP in the past 3 months) will be recruited from the University population and local community (total study sample size n=40).

The sample size of the LBP group was estimated using a power calculation based upon the EMG outcome. To complete this calculation, data from a previous study which is currently under-review for publication was used - ERN_17-0782, this study was used because the methodology and measurement outcomes are similar to those described herein. A projected total sample size of 36 (a priori calculation with GPower 3.1 using an ANOVA with an effect size of 0.5, $\alpha = .05$, power $(1-\beta) = 0.8$, a sample size of 18 per group will be required. The sample size is increased to 20 per group to allow for possible drop-outs.

Exclusion criteria for the LBP group includes spinal surgery, spinal fractures, scoliosis major respiratory or neurological conditions, recent or current pregnancies, back pain radiating below the buttock, current treatment for LBP by a health care professional, prescription strength medications such as opioids, anticonvulsives, or regular high-dosed anti-inflammatories.

Exclusion criteria for the control group will include any history of spinal surgery or fractures, major respiratory or neurological conditions, recent or current pregnancies, any pain which radiates down the leg, prescription strength medications such as opioids, anticonvulsives, or regular high-dosed anti-inflammatories. Additionally, participants will be excluded if they have had any LBP in in at least 5 years which has required treatment from a health care practitioner or report any history of low back pain in the last 3 months.

10. RECRUITMENT

Please state clearly how the participants will be identified, approached and recruited. Include any relationship between the investigator(s) and participant(s) (e.g. instructor-student).

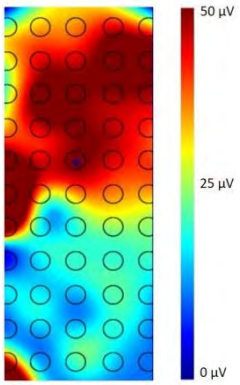
Note: Attach a copy of any poster(s), advertisement(s) or letter(s) to be used for recruitment.

Participants from the community and population of staff and students at the University of Birmingham will be recruited via poster advertisement at the University of Birmingham campuses, affiliated social media, and through the CPR Spine Register.

Interested volunteers will be asked to contact Andy Sanderson or Prof Deborah Falla through email, telephone or face to face. Additionally, members of the CPR Spine Register, who have consented to be informed when research relevant to their spinal condition is being conducted, will be contacted. Relevant members of the register will be contacted by someone with no connection to the project and will be supplied with a participant information form, recruitment poster and short biography of the project. Any member of the register who is contacted will be advised that if they are interested they should contact the investigators directly, equally they will be advised that if they are not interested or not able to participate then they do not need to reply and this decision will have no impact on their membership to the register. An example of an email which would be sent to participants is included below;

Hello,
We would like to invite individuals with chronic non-specific low back pain to participate in a lab based study at CPR Spine. This study will take approximately 4 hours in total, spread across two sessions between 72 hours to 1 week apart at a time that suits you.
This study aims to use a novel technique to allow participants to understand how their muscles are contracting in real-time and investigate if it is possible to make changes to this pattern. We also ask you some questions about you, your back pain, and activities you do doing your everyday life. You are under no obligation to take part. The project has full ethical approval from the University of Birmingham.

What will I have to do?
We will measure the activity of your back muscles and collect information on how you move while completing functional tasks. The first task involves moving a 5kg box between different shelves and the second task is an endurance task for your lower back where you will be asked to maintain a position until you feel like you are no longer able to hold it.
We will also allow you to 'see' your muscle activity in the form of a colour map (Example shown in image) and we will help you to alter your activation pattern using this information during the same tasks. To understand how you activate your muscles and move, we will place sensors and markers on your skin.



What are the benefits?
You will also gain a better understanding of how your back muscles activate and how this may be linked to pain that you are experiencing.

What happens to the information?
All information obtained from you will be kept strictly confidential. You will be asked to complete a consent form at the CPR Spine lab after the experiment has been fully explained to you and any questions have been answered. All data for presentation will be anonymised, that means your identity will not be revealed in any way. The findings from this study will be presented, or shared with other researchers in the form of presentations and scientific papers as appropriate.

Who else is taking part?
This study will compare the results of both men and women with chronic non-specific low back pain with those of pain-free controls of similar age and gender distribution.

If I take part, do I get paid?
You will be compensated £20 per session for your time, to a total of £40 for completing both sessions.

What if I have more questions, do not understand something or wish to take part?
If you have any questions or would like to express your interest in taking part in this study, please contact Andy at or call on

Thank you for your help with our study.
Best wishes,

All information regarding the experiment will be provided in the 'Participant Information Leaflet', which will be sent or given to volunteers who indicated their interest. The researchers involved in this project will explain the experimental measures and the exercise intervent ion to the participants and answer any questions they may have. The investigators' telephone and e-mail references will be provided on the 'Participant Information Leaflet'. This leaflet summarises the protocol and requirements of the study. Following an expression of interest, the participant will be screened by one of the research team to assess eligibility and answer any questions the participant may have about the study.

11. CONSENT

a) Describe the process that the investigator(s) will be using to obtain valid consent. If consent is not to be obtained explain why**.** If the participants are minors or for other reasons are not competent to consent, describe the proposed alternate source of consent, including any permission / information letter to be provided to the person(s) providing the consent.

Prior to participating in the study, the 'Participant Information Leaflet' will be handed out again, summarised and discussed. Then a written consent form will be read and signed by all participants. This includes information about data storage and that data will only be used for the purpose of research, statistical and audit purposes by the University of Birmingham in accordance with the General Data Protection Regulation (GDPR) 2018 and the University of Birmingham Research guidelines.

Note: Attach a copy of the Participant Information Sheet (if applicable), the Consent Form (if applicable), the content of any telephone script (if applicable) and any other material that will be used in the consent process.

b) Will the participants be deceived in any way about the purpose of the study? **Yes** ☐ **No** ☒

If yes, please describe the nature and extent of the deception involved. Include how and when the deception will be revealed, and who will administer this feedback.

12. PARTICIPANT FEEDBACK

Explain what feedback/ information will be provided to the participants after participation in the research. (For example, a more complete description of the purpose of the research, or access to the results of the research).

A summary of the study will be offered to participants via email after the completion of the entire study and data analysis.

Participants with LBP will also be invited to join the spinal register at the completion of the project, however they will be informed that any decision to join is voluntary and has no bearing on anything external to the register.

13. PARTICIPANT WITHDRAWAL

a) Describe how the participants will be informed of their right to withdraw from the project.

Participants will have the opportunity to withdraw from the study at any point and up to two weeks following completion of data collection without having to give a reason. This will be stated on the participant information sheet and written consent form with contact details provided.

b) Explain any consequences for the participant of withdrawing from the study and indicate what will be done with the participant's data if they withdraw.

There will be no consequences if a participant chooses to withdraw from the study. Participants will be informed that all data collected up to point of withdrawal will be included in data analysis unless the participant specifies otherwise.

14. COMPENSATION

Will participants receive compensation for participation?

i) Financial **Yes** ☒ **No** ☐

ii) Non-financial **Yes** ☒ **No** ☐

If **Yes** to **either** i) or ii) above, please provide details.

All participants will be free to choose between research hours or financial compensation. If Participants elect to receive research hours they will not receive financial compensation as well.

If participants require research hours for completion of a taught module, they will be offered research hours at a rate of 1 research hour per hour of the project. If they opt for financial compensation, participants will receive a total of £40 compensation for completing this study, or a £20 fixed rate for each session of the study which they complete.

If participants choose to withdraw, how will you deal with compensation?

If participants choose to withdraw, they will be offered partial compensation which is determined by the amount of time the participant was present in the Lab before withdrawal. Partial compensation will be calculated at a rate of £2.50 per 15 minutes of the uncompleted session, to a maximum of £20 per session. Research hours will be calculated by each part-hour completed.

15. CONFIDENTIALITY

a) Will all participants be anonymous? **Yes** ☐ **No** ☒

b) Will all data be treated as confidential? **Yes** ☒ **No** ☐

Note: Participants' identity/data will be confidential if an assigned ID code or number is used, but it will not be anonymous. Anonymous data cannot be traced back to an individual participant.

Describe the procedures to be used to ensure anonymity of participants and/or confidentiality of data both during the conduct of the research and in the release of its findings.

All participants will be allocated an ID number to enable pseudo-anonymisation. Only necessary personal data will be collected during the study, including name, contact telephone number and email address. This information will be collected on the consent form for the study, which will be securely stored in Prof. Falla's Office.

All data collected will be kept securely locked in a cabinet or saved on a University of Birmingham secured network and remains strictly confidential throughout. The data will only be shared with the participant, investigator and research team. It will not be given to a third party, and it will be stored for 10 years in line with University of Birmingham Research Governance guidelines. All data will be collected and stored under the identification number allocated at the point of recruitment.

If participant anonymity or confidentiality is not appropriate to this research project, explain, providing details of how all participants will be advised of the fact that data will not be anonymous or confidential.

16. STORAGE, ACCESS AND DISPOSAL OF DATA

Describe what research data will be stored, where, for what period of time, the measures that will be put in place to ensure security of the data, who will have access to the data, and the method and timing of disposal of the data.

All data will be stored securely in electronic format. Access to data will require a password and all data will be managed in accordance with the GDPR 2018. The investigators will have access to the anonymised data.
Following the completion of data collection, all consent forms containing personal data will be securely stored in a locked filing cabinet in Prof. Falla's office and can only be accessed by the investigators.
Data will be kept for 10 years under the University's Code of Practice for Research.

17. OTHER APPROVALS REQUIRED? e.g. Criminal Records Bureau (CRB) checks or NHS R&D approvals.

☐ YES ☒ NO ☐ NOT APPLICABLE

If yes, please specify.

18. SIGNIFICANCE/BENEFITS

Outline the potential significance and/or benefits of the research

This study will enhance our understanding of LBP and will provide information which can form the basis for future biofeedback studies. Previous investigations have enhanced understanding of muscle activation in LBP, however the basis to correct the differences seen in previous studies remains unknown. This study will assess if participants are able to change their activation pattern based on the HDEMG biofeedback and the influence of this on subjective and objective measures of performance. If this technique of biofeedback is possible, it could pave the way for innovation in the field of wearable technology and patient care.

19. RISKS

a) Outline any potential risks to **INDIVIDUALS**, including research staff, research participants, other individuals not involved in the research and the measures that will be taken to minimise any risks and the procedures to be adopted in the event of mishap

HDEMG
While there are no expected risks, it is noted that the HDEMG device being used is still in development and as such is not CE marked for safety. The developers were contacted for evidence of safety tests and provided the following information;

"The Meacs system is not (yet) CE marked because it is a very new device. We plan to start the procedures for the CE mark in collaboration with OT Bioelettronica very soon, during the technology transfer phase.

However, the system is battery powered (600mAh 4.2V 1-Cell LiPo Battery) and thus floating with respect to ground. For this reason, we can state that the basic safety of the instrument is guaranteed both in normal and single fault conditions as defined by the general standard (IEC 60601-1 - Medical electrical equipment - Part 1: General requirements for basic safety and essential performance).

We measured the patient and earth leakage current in normal and single fault conditions as defined by the IEC 60601-1 standard and using the Rigel 288+ Electrical Safety Analyzer. All the performed tests showed that leakage currents are below the resolution of the Rigel 288+ (4μA) and the stricter limit imposed by EU regulations (10μA)."

Kinematics/Biofeedback
No expected risks

Functional Tasks
These tasks include both static and dynamic contractions which are common to daily activities and have been used safely before in our previous studies (Static - ERN_17-0782; Dynamic - ERN_16-1389B), and as such should carry no higher risk than any other day-to-day activity or physical exercise. Participants will however be advised to immediately stop the task and rest until they feel able to continue and they will also have the option to stop and withdraw from the study at any time. Similar protocols have been successfully used previously in a LBP population, therefore it is anticipated that the LBP group will complete the study without exacerbation. Participants will be monitored carefully for symptom reproduction by the research team.

b) Outline any potential risks to **THE ENVIRONMENT and/or SOCIETY** and the measures that will be taken to minimise any risks and the procedures to be adopted in the event of mishap.

None

20. ARE THERE ANY OTHER ETHICAL ISSUES RAISED BY THE RESEARCH?

Yes ☐ **No** ☒

If yes, please specify

21. EXPERT REVIEWER/OPINION

You may be asked to nominate an expert reviewer for certain types of project, including those of an interventional nature or those involving significant risks. If you anticipate that this may apply to your work and you would like to nominate an expert reviewer at this stage, please provide details below.

Name
Contact details (including email address)
Brief explanation of reasons for nominating and/or nominee's suitability

22. CHECKLIST

Please mark if the study involves any of the following:

- Vulnerable groups, such as children and young people aged under 18 years, those with learning disability, or cognitive impairments ☐
- Research that induces or results in or causes anxiety, stress, pain or physical discomfort, or poses a risk of harm to participants (which is more than is expected from everyday life) ☒
- Risk to the personal safety of the researcher ☐
- Deception or research that is conducted without full and informed consent of the participants at time study is carried out ☐
- Administration of a chemical agent or vaccines or other substances (including vitamins or food substances) to human participants. ☐
- Production and/or use of genetically modified plants or microbes ☐
- Results that may have an adverse impact on the environment or food safety ☐
- Results that may be used to develop chemical or biological weapons ☐

Please check that the following documents are attached to your application.

	ATTACHED	NOT APPLICABLE
Recruitment advertisement	☒	☐
Participant information sheet	☒	☐
Consent form	☒	☐
Questionnaire	☐	☒
Interview Schedule	☐	☒

23. DECLARATION BY APPLICANTS

I submit this application on the basis that the information it contains is confidential and will be used by the University of Birmingham for the purposes of ethical review and monitoring of the research project described herein, and to satisfy reporting requirements to regulatory bodies. The information will not be used for any other purpose without my prior consent.

I declare that:

- The information in this form together with any accompanying information is complete and correct to the best of my knowledge and belief and I take full responsibility for it.
- I undertake to abide by University Code of Practice for Research (http://www.as.bham.ac.uk/legislation/docs/COP_Research.pdf) alongside any other relevant professional bodies' codes of conduct and/or ethical guidelines.
- I will report any changes affecting the ethical aspects of the project to the University of Birmingham Research Ethics Officer.
- I will report any adverse or unforeseen events which occur to the relevant Ethics Committee via the University of Birmingham Research Ethics Officer.

Name of principal investigator/project supervisor:	Deborah Falla
Date:	26/7/18

Please now save your completed form, print a copy for your records, and then email a copy to the Research Ethics Officer, at aer-ethics@contacts.bham.ac.uk. As noted above, please do not submit a paper copy.

UNIVERSITY OF BIRMINGHAM
APPLICATION FOR ETHICAL REVIEW – REQUEST FOR AMENDMENTS

Who should use this form:

- This form is to be completed by PIs or supervisors (for PGR student research) who are requesting ethical approval for amendments to research projects that have previously received ethical approval from the University of Birmingham.

  Please be aware that all new research projects undertaken by postgraduate research (PGR) students first registered as from 1st September 2008 will be subject to the University's Ethical Review Process. PGR students first registered before 1st September 2008 should refer to their Department/School/College for further advice.

- What constitutes an amendment?

  Amendments requiring approval may include, but are not limited to, additions to the research protocol, study population, recruitment of participants, access to personal records, research instruments, or participant information and consent documentation. Amendments must be approved before they are implemented.

NOTES:

- Answers to questions must be entered in the space provided
- An electronic version of the completed form should be submitted to the Research Ethics Officer, at the following email address: aer-ethics@contacts.bham.ac.uk. Please **do not** submit paper copies.
- If, in any section, you find that you have insufficient space, or you wish to supply additional material not specifically requested by the form, please submit it in a separate file, clearly marked and attached to the submission email.
- If you have any queries about the form, please address them to the Research Ethics Team.

UNIVERSITY OF BIRMINGHAM APPLICATION FOR ETHICAL REVIEW - REQUEST FOR AMENDMENTS	*OFFICE USE ONLY:* Application No: Date Received:

1. **TITLE OF PROJECT**

Can detailed biofeedback on muscle activity enhance subjective and objective markers of performance in people with and without low back pain?

2. **APPROVAL DETAILS**

What is the Ethical Review Number (ERN) for the project?

ERN_18-1261

3. **THIS PROJECT IS:**

University of Birmingham Staff Research project ☐
University of Birmingham Postgraduate Research (PGR) student project ☒
Other ☐ (Please specify):

4. **INVESTIGATORS**

d) PLEASE GIVE DETAILS OF THE PRINCIPAL INVESTIGATORS OR SUPERVISORS (FOR PGR STUDENT PROJECTS)

Name: Title / first name / family name	Professor Deborah Falla
Highest qualification & position held:	Chair in Rehabilitation Science and Physiotherapy
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

Name: Title / first name / family name	Dr. Alison Rushton
Highest qualification & position held:	Reader
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

Name: Title / first name / family name	Dr. Nicola Heneghan
Highest qualification & position held:	Lecturer
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

e) PLEASE GIVE DETAILS OF ANY CO-INVESTIGATORS OR CO-SUPERVISORS (FOR PGR STUDENT PROJECTS)

Name: Title / first name / family name	Dr. Eduardo Martinez Valdes
Highest qualification & position held:	Lecturer
School/Department	School of Sport, Exercise and Rehabilitation Sciences
Telephone:	
Email address:	

f) In the case of PGR student projects, please give details of the student

Name of student:	Andy Sanderson	Student No:
Course of study:	PhD	Email address:
Principal supervisor:	Prof. Falla	

5. **ESTIMATED START OF PROJECT** Date: 01/09/18

ESTIMATED END OF PROJECT Date: 31/12/2019

6. **ORIGINAL APPLICATION FOR ETHICAL REVIEW AND ANY SUBSEQUENT APPROVED AMENDMENTS:**

Please complete the table below for the original application and any subsequent amendments submitted

Title and reference number of application or amendment	**Key points of application and/or changes made by amendment (include: aims of study, participant details, how participants were recruited and methodology)**	**Ethical considerations arising from these key points (e.g. gaining consent, risks to participants and/or researcher, points raised by Ethical Review Committee during review)**	**How were the ethical considerations addressed? (e.g. consent form, participant information, adhering to relevant procedures/clearance required)**
Original application	Objectives 3. To investigate whether people with LBP can modify the distribution of lumbar Erector Spinae (ES) activity based on detailed feedback from HDEMG. 4. To investigate whether detailed HDEMG biofeedback can modify both patient reported outcomes (fatigue, pain) and performance based outcomes (endurance) while completing static and dynamic tasks 20 Participants with low back pain and 20 healthy controls were to be recruited to participate in an experiment investigating the effect of detailed biofeedback on muscle activity. Participants were to be recruited from the University of Birmingham community, the CPR Spine register and using social media outlets affiliated to the University. This project will use high-density EMG to create real-time colourised maps of the muscle activity in the participant which would then be displayed as a form of biofeedback to one group of participants to investigate how this affects their ability to redistribute muscle activity. Originally it was proposed to display these during both a static and a very dynamic task	- The CE status of the wireless EMG electrodes was enquired about as the devices are still prototypes - It was asked if a female investigator could also be present for any female participants who may feel uncomfortable - Copies of the questionnaires which would be administered were requested - The community recruitment procedure was questioned, with particular reference to recruitment through the CPR Spine register	- The devices were included in the H&S paperwork, and as the devices are small and wireless there is limited electricity present, they have also been tested and the values were in line or better than the current minimum required within the EU. - As this study does not require the participant to undress, this should not be an issue, however a provision was added that if a participant requests this then a female examiner will be present. - The requested paperwork was provided for review. - The wording of these messages and how this would be completed was provided to the ethical committee for review

7. **DETAILS OF PROPOSED NEW AMENDMENT**
Provide details of the proposed new amendment, and clearly and explicitly state how the proposed new amendment will differ from the details of the study as already approved (see Q6 above).

The dynamic task previously approved is very demanding, and as such we hope to add in a simpler dynamic task to evaluate the system initially. This task will comprise of postural correction, in that participants will be asked to move from a slouched position to a more upright position when sitting on a stool. During the first session, participants will be trained by a qualified and experienced physiotherapist how to improve their technique, we expect that this training will focus on reducing thoracolumbar extension of the spine in favour of lumbar extension. One group will have the muscle activity of their lumbar spine displayed in the form of biofeedback and one group will not, so as to compare the effect of the biofeedback to enhance the physiotherapist training. Following this training, participants will again be asked to correct their posture and differences between groups recorded. In the second session, following a wash-out period, participants will be asked to again correct their posture, one group still with biofeedback and this will be recorded with the EMG to investigate if there are any differences between groups in their recall at a later session.

Similarly, we hope to reduce the strenuousness of the static task, while the protocol will remain the same, the duration the task will no longer be to exhaustion/5 minutes. In lieu of this, we instead intend to perform three 30 second extension tasks in this position, one at the start of the first session, one at the end of the first session with biofeedback for one group and one at the end of the second session with biofeedback for one group. The combination of this and the posture corrections will hereafter be referred to as the 'postural component'.

As the tasks completed in the posture component will be less strenuous, we would like to investigate the effects at a shorter time interval. Previously, the two sessions were intended to be between 72h-1 week apart, however with the changes detailed above we would like to reduce this time to between 18-48h for the postural component only. If the dynamic task or the static task as approved previously were to be used in a future study then this time interval would revert back to 72h-1 week.

As the postural component outlined above will take less time than the tasks approved previously we would suggest that for completion of the postural task component only, the compensation reflects this shorter duration and is paid at £10/session and £20 on completion of both aspects.

Additionally, the kinematics equipment will also be supplemented, to allow ease of data collection. In addition to the BTE system currently included, we would like to gain approval for a new kinematic system by Noraxon, comprising of Noraxon Mobile lab IMU's (Noraxon, USA, CE marked). These sensor units contain gyroscopic sensors which allow for the measurement of the individual body segments which they are attached to. The units have purpose made Velcro straps which are built to house them and attach to the participant. This will however require additional measurement of anthropological data from the participant, including the lengths of the body segments which we will be using e.g. leg length.

8. **JUSTIFICATION FOR PROPOSED NEW AMENDMENT**

Following pilot testing, it has been determined that the dynamic task included in the original ethical approval is too dynamic for the biofeedback system at this point. While we do still intend to progress to this stage, we hope to use the postural correction task to investigate how effective the biofeedback is during a simple dynamic task which is commonly administered by physiotherapists. Following completion of this study we hope to have a better understanding of the possibilities of this biofeedback system and progress to more dynamic or demanding tasks with consideration to these results.

The lumbar extension task is designed to provide information about how the participant activates the lumbar musculature throughout a fatiguing contracting. However as the postural component focusses on specifically training participants to increase muscle activity in the lumbar region only, we hope to investigate here how well the training can be translated outside of that specific setting. Our previous results showed the participants who contracted more of the lumbar musculature were able to sustain the task for a longer duration, as this activation is similar to what is being achieved by the training we hope to investigate how this affects muscle activity distribution and redistribution and if this is improved with the biofeedback. However to understand the differences in activity at

various stages, rather than ask participants to complete several fatiguing contractions, we have instead decided to ask for the completion of shorter contractions from which we can infer longer duration results from.

The tasks outlined within the postural component will take a much shorter duration, and will be less fatiguing than the previously approved tasks. As a result, we expect that the experimental sessions will take approximately 2 hours in total rather than the 2h per session previously estimated. As the tasks are less fatiguing and the outcomes more subtle we hope to retest sooner than previously suggested to avoid participants forgetting their training and the effects being lost. In line with this shorter duration we also would like to adjust the compensation to reflect the reduced time burden on participants.

The use of the BTS kinematics system requires the booking of a specific lab which is known to often be in high demand. In order to allow data collection to proceed without these issues, we hope to be able to use the newly acquired and highly mobile Noraxon system, which can be used in any lab.

9. **ETHICAL CONSIDERATIONS**

What ethical considerations, if any, are raised by the proposed new amendment?

The use of the Noraxon system will require additional collection of anthropological data, however this is in line with previous studies which use these standard measurements for the Davis kinematics protocol (Davis et al., 1991). The data collected will be stored securely along with all other participant data in a locked filing cabinet at the CPR Spine office.

The addition of the postural component should have no additional ethical considerations. The training will be completed by a trained physiotherapist and the tasks which will be completed are less fatiguing than those previously approved.

10. DECLARATION BY APPLICANTS

I make this application on the basis that the information it contains is confidential and will be used by the University of Birmingham for the purposes of ethical review and monitoring of the research project described herein, and to satisfy reporting requirements to regulatory bodies. The information will not be used for any other purpose without my prior consent.

I declare that:

- The information in this form together with any accompanying information is complete and correct to the best of my knowledge and belief and I take full responsibility for it.
- I undertake to abide by University Code of Conduct for Research (http://www.birmingham.ac.uk/Documents/university/legal/research.pdf) alongside any other relevant professional bodies' codes of conduct and/or ethical guidelines.
- I will report any changes affecting the ethical aspects of the project to the University of Birmingham Research Ethics Officer.
- I will report any adverse or unforeseen events which occur to the relevant Ethics Committee project to the University of Birmingham Research Ethics Officer.

Signature of Principal investigator/project supervisor:	
Date:	

Andrew Sanderson (PhD School of Sprt+Ex Scie FT)

From: Samantha Waldron (Research Support Group) <S.M.Waldron@bham.ac.uk>
Sent: 10 September 2018 13:24
To: Deborah Falla (School of Sport Exercise and Rehabilitation Sciences); Alison Rushton (Physiotherapy); Nicola Heneghan (Physiotherapy)
Cc: 'a.sanderson@pgr.bham.ac.uk'
Subject: Application for Ethical Review ERN_18-1261

Follow Up Flag: Follow up
Flag Status: Flagged

Dear Professor Deborah Falla, Dr. Alison Rushton & Dr. Nicola Heneghan,

Re: "Can detailed biofeedback on muscle activity enhance subjective and objective markers of performance in people with and without low back pain?"
Application for Ethical Review ERN_18-1261

Thank you for your application for ethical review for the above project, which was reviewed by the Science, Technology, Engineering and Mathematics Ethical Review Committee.

On behalf of the Committee, I confirm that this study now has full ethical approval.

I would like to remind you that any substantive changes to the nature of the study as described in the Application for Ethical Review, and/or any adverse events occurring during the study should be promptly bought to the Committee's attention by the Principal Investigator and may necessitate further ethical review.

Please also ensure that the relevant requirements within the University's Code of Practice for Research and the information and guidance provided on the University's ethics webpages (available at https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research-Ethics/Links-and-Resources.aspx) are adhered to and referred to in any future applications for ethical review. It is now a requirement on the revised application form (https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research-Ethics/Ethical-Review-Forms.aspx) to confirm that this guidance has been consulted and is understood, and that it has been taken into account when completing your application for ethical review.

Please be aware that whilst Health and Safety (H&S) issues may be considered during the ethical review process, you are still required to follow the University's guidance on H&S and to ensure that H&S risk assessments have been carried out as appropriate. For further information about this, please contact your School H&S representative or the University's H&S Unit at healthandsafety@contacts.bham.ac.uk.

Kind regards,

Ms Sam Waldron
Deputy Research Ethics Officer
Research Support Group
C Block Dome (room 132)
Aston Webb Building
University of Birmingham
Edgbaston B15 2TT

1

Can detailed biofeedback on muscle activity enhance subjective and objective markers of performance in people with and without low back pain?

We are looking for volunteers to take part in a research study. Before you decide whether you would like to take part, it is important that you know what the study is about and what it would involve for you. This is explained below; please read the information carefully.

WHAT IS THE STUDY ABOUT?

Research has shown that changes can occur in the back muscles of people who have ongoing or chronic low back pain (LBP). This could include a change in the way in which people activate these muscles, whereby people with LBP use an activation pattern which appears to lead to greater fatigue in the muscle and worse functional outcomes e.g. less endurance. What is not known, is how these activation patterns could be corrected in people with LBP, and if this was possible, what the effects of this change would be. This study aims to use a novel technique to allow participants to understand how their muscles are contracting in real-time and investigate if it is possible to make changes to this pattern.

CAN I PARTICIPATE?

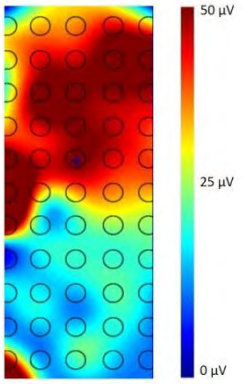
You can participate if you are between 18 and 55 years old and you have had no LBP in the last 5 years which has needed treatment by a health care practitioner or any recent history of LBP in the last 3 months. You must also ***not*** fall in any of the categories below:

Pain from your back referring down your leg; spinal surgery, spinal fractures, recent or current pregnancies, major neurological or cardiorespiratory conditions, receiving LBP treatment at the time of the study (e.g. physiotherapy, chiropractic) or taking certain medications (e.g. opioids, anticonvulsives, or regular high-dose anti-inflammatories).

We will ask you to complete a brief screening assessment to ensure you are eligible to participate. This will be performed by an experienced researcher and will include questions about your general health.

WHAT WILL I HAVE TO DO IF I PARTICIPATE?

We will ask that you to attend two data collection sessions, taking approximately 1h30 per session, these sessions can be organised at a time that will suit you, and will be between 18-48 hours apart. During these sessions, we will measure the activity of your back muscles and collect information on how you move while completing functional tasks. The tasks will involve a short lumbar extension task (30secs) repeated three times, and some postural correction from a seated position. Additionally, during the first session, a physiotherapist will train you on how to optimally adjust your posture.



You may be able to 'see' your muscle activity in the form of a colour map (Example shown in image) and we will help you to understand your activation pattern using this information. To measure how you activate your muscles and move, we will place sensors and markers on your skin. We will ask you to bring shorts and a top that leaves your back accessible for this session which will take place in the CPR Spine labs.

HOW MUCH TIME WILL I HAVE TO SPEND IN TOTAL?

The screening assessment and questionnaires will require approximately 20 minutes, most of which can be completed prior to the session. Data collection in the lab will last approximately 1 hour, which will be a total of 2 hours in the two sessions.

ARE THERE ANY BENEFITS FOR ME IF I TAKE PART?
You will also gain a better understanding of how your back muscles activate and how biofeedback can be used to increase performance.

ARE THERE ANY RISKS FOR ME IF I TAKE PART?
The risks are low, as all procedures are carried out by experienced professionals and you will be thoroughly screened to ensure that it is safe for you to take part. All tests performed are non-invasive. If, however you feel any discomfort or pain during any aspect of the study, then you will be free to stop and should you wish, you can withdraw from the study.

ARE THERE ANY COST OR REIMBURSEMENTS FOR ME?
There is no cost for this study, but you will be compensated £10 per session for your time, to a total of £20 for completing both sessions. Alternatively, you can claim up to 3 research hours for participating in this study.

DO I HAVE TO TAKE PART?
No, participation is entirely voluntary. If you decide to take part but you change your mind, you can withdraw from the study at any time, without having to give a reason.

WILL MY DATA BE KEPT CONFIDENTIAL?
All information collected on you will be kept strictly confidential. The consent form containing your allocated ID will never be present in electronic form, will be securely stored within CPR Spine and only available to the researchers. All data will be stored for 10 years managed in accordance with the EU General Data Protection Regulation 2018 and the University of Birmingham Research Guidelines.

WHAT WILL HAPPEN TO THE RESULTS OF THE STUDY?
All data for presentation will be anonymised, that means your identity will not be revealed in any way. The findings from this study will be presented, or shared with other researchers in the form of presentations and scientific papers as appropriate.

DOES THE STUDY FOLLOW ETHICS PROCEDURES?
This study underwent the ethical review processes of the University of Birmingham and received official approval from the University Ethics Committee.

WHO IS ORGANISING AND FUNDING THE RESEARCH?
The study has been designed and organised by Andy Sanderson and is overseen by Professor Deborah Falla, Chair in Rehabilitation Science and Physiotherapy (

For further information please contact Andy Sanderson

Andy Sanderson Centre of Precision Rehabilitation for Spinal Pain School of Sports, Exercise and Rehabilitation Sciences University of Birmingham B15 2TT	

Thank you for taking the time to read this and considering taking part in the study!

Can detailed biofeedback on muscle activity enhance subjective and objective markers of performance in people with and without low back pain?

We are looking for volunteers to take part in a research study. Before you decide whether you would like to take part, it is important that you know what the study is about and what it would involve for you. This is explained below; please read the information carefully.

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Research has shown that changes can occur in the back muscles of people who have ongoing or chronic low back pain (LBP). This could include a change in the way in which people activate these muscles, whereby people with LBP use an activation pattern which appears to lead to greater fatigue in the muscle and worse functional outcomes e.g. less endurance. What is not known, is how these activation patterns could be corrected in people with LBP, and if this was possible, what the effects of this change would be. This study aims to use a novel technique to allow participants to understand how their muscles are contracting in real-time and investigate if it is possible to make changes to this pattern.

CAN I PARTICIPATE?

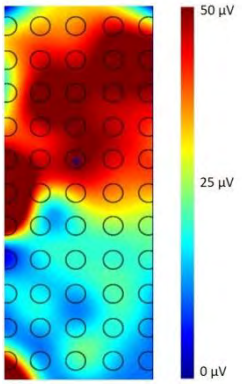
You can participate if you are between 18 and 55 years old and you have had LBP which you don't know the cause of (i.e. with no diagnosis) for more than half the days of the last 6 months. You must also ***not*** fall in any of the categories below:

Acute LBP or LBP with a diagnosis or known pathology, such as disc herniation; pain from your back referring down your leg; spinal surgery, spinal fractures, recent or current pregnancies, major neurological or cardiorespiratory conditions, receiving LBP treatment at the time of the study (e.g. physiotherapy,) or taking certain medications (e.g. opioids, anticonvulsives, or regular high-dose anti-inflammatories).

We will ask you to complete a brief screening assessment to ensure you are eligible to participate. This will be performed by an experienced researcher and will include questions about your general health and LBP.

WHAT WILL I HAVE TO DO IF I PARTICIPATE?

We will ask that you to attend two data collection sessions, taking approximately 1h30 per session, these sessions can be organised at a time that will suit you, and will be between 18-48 hours apart. During these sessions, we will measure the activity of your back muscles and collect information on how you move while completing functional tasks. The tasks will involve a short lumbar extension task (30secs) repeated three times, and some postural correction from a seated position. Additionally, during the first session, a physiotherapist will train you on how to optimally adjust your posture.



You may be able to 'see' your muscle activity in the form of a colour map (Example shown in image) and we will help you to understand your activation pattern using this information. To measure how you activate your muscles and move, we will place sensors and markers on your skin. We will ask you to bring shorts and a top that leaves your back accessible for this session which will take place in the CPR Spine labs.

HOW MUCH TIME WILL I HAVE TO SPEND IN TOTAL?

The screening assessment and questionnaires will require approximately 20 minutes, most of which can be completed prior to the session. Data collection in the lab will last approximately 1 hour, which will be

a total of 2 hours in the two sessions.

ARE THERE ANY BENEFITS FOR ME IF I TAKE PART?
You will also gain a better understanding of how your back muscles activate and how this may be linked to pain that you are experiencing.

ARE THERE ANY RISKS FOR ME IF I TAKE PART?
The risks are low, as all procedures are carried out by experienced professionals and you will be thoroughly screened to ensure that it is safe for you to take part. All tests performed are non-invasive. If, however you feel any discomfort or pain during any aspect of the study, then you will be free to stop and should you wish, you can withdraw from the study.

ARE THERE ANY COST OR REIMBURSEMENTS FOR ME?
There is no cost for this study, but you will be compensated £10 per session for your time, to a total of £20 for completing both sessions. Alternatively, you can claim up to 3 research hours for participating in this study.

DO I HAVE TO TAKE PART?
No, participation is entirely voluntary. If you decide to take part but you change your mind, you can withdraw from the study at any time, without having to give a reason.

WILL MY DATA BE KEPT CONFIDENTIAL?
All information collected on you will be kept strictly confidential. The consent form containing your allocated ID will never be present in electronic form, will be securely stored within CPR Spine and only available to the researchers. All data will be stored for 10 years managed in accordance with the EU General Data Protection Regulation 2018 and the University of Birmingham Research Guidelines.

WHAT WILL HAPPEN TO THE RESULTS OF THE STUDY?
All data for presentation will be anonymised, that means your identity will not be revealed in any way. The findings from this study will be presented, or shared with other researchers in the form of presentations and scientific papers as appropriate.

DOES THE STUDY FOLLOW ETHICS PROCEDURES?
This study underwent the ethical review processes of the University of Birmingham and received official approval from the University Ethics Committee.

WHO IS ORGANISING AND FUNDING THE RESEARCH?
The study has been designed and organised by Andy Sanderson and is overseen by Professor Deborah Falla, Chair in Rehabilitation Science and Physiotherapy

For further information please contact Andy Sanderson

Andy Sanderson Centre of Precision Rehabilitation for Spinal Pain School of Sports, Exercise and Rehabilitation Sciences University of Birmingham B15 2TT	

Thank you for taking the time to read this and considering taking part in the study!

Consent Form

Study ID:

Can detailed biofeedback on muscle activity enhance subjective and objective markers of performance in people with and without low back pain?

This information is being collected as part of a research project concerned with the investigation of changes in pain sensitivity due to repeated exercise sessions by the Centre of Precision Rehabilitation of Spinal Pain within the School of Sport, Exercise and Rehabilitation Sciences at the University of Birmingham. The information which you supply and that which may be collected as part of the research project will be entered into a filing system or database and will only be accessed by authorised personnel involved in the project. The information will be retained by the University of Birmingham and will only be used for the purpose of research and statistical and audit purposes. By supplying this information you are consenting to the University storing your information for the purposes stated above. The information will be processed by the University of Birmingham in accordance with the provisions of the EU General Data Protection Regulation 2018. No identifiable personal data will be published.

Please initial each box if you agree with the statement and sign the form

	I confirm that I have read and understand the participant information leaflet for this study. I have had the opportunity to ask questions if necessary and have had these answered satisfactorily.
	I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason as I will have the right to withdraw my data from the study up to two weeks following completion of data collection. If I withdraw my data will be removed from the study and will be destroyed. Participants will be free to withdraw at any time during the experimental session.
	I understand that my personal data will be processed for the purposes detailed above, in accordance with the EU General Data Protection Regulation 2018.
	Based upon the above, I agree to take part in this study.

Name of participant…… Date…… Signature……..

Name of researcher/ individual obtaining consent…… Date…… Signature……..

<u>Contact details of participant</u>

Contact number: Email address:

Appendix 12 – Modified Pain Self Efficacy Questionnaire

Pain Management Self-Efficacy

Efficacy is defined as 'the ability to produce a desired or intended result.'

People sometimes do things to change their muscle activity which might reduce their pain without taking medication.

Please rate how certain you are that you can achieve these changes in muscle activity and/or reduce the different levels of pain described below?

Rate your degree of confidence by recording a number from 0 to 100 using the scale given below:

0 10 20 30 40 50 60 70 80 90 100

Cannot do at all Moderately can do Highly certain can do

Altering Muscle Activity Confidence (0-100)

How confident are you that you can….

Alter the way in which you contract your muscles _____

Alter the way in which the muscles in your back contract _____

Specifically focus on a region of the back to contract that region more _____

Specifically focus on a region of the lower back to contract that region more_____

Adjust the way you move to change how you use your muscles _____

Use visual feedback to change how you use your muscles _____

Use Physiotherapist feedback to change how you use your muscles _____

Pain Reduction

To what extent do you think that changing your muscle activity will…

Reduce a DULL PAIN

A small reduction _____

A moderate reduction _____

A large reduction _____

Reduce an ACHING PAIN

A small reduction _____

A moderate reduction _____

A large reduction _____

Reduce a PENETRATING PAIN

A small reduction _____

A moderate reduction _____

A large reduction _____

Reduce an EXCRUCIATING PAIN

A small reduction _____

A moderate reduction _____

A large reduction _____

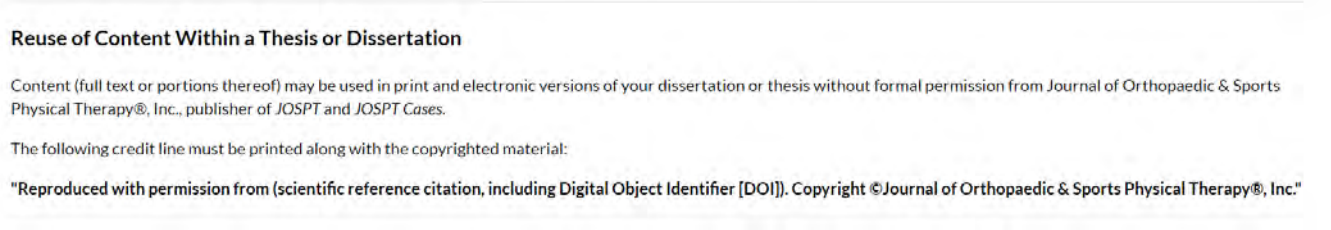
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Chapter Four

SANDERSON, A., CESCON, C., HENEGHAN, N. R., KUITHAN, P., MARTINEZ-VALDES, E., RUSHTON, A., BARBERO, M., FALLA, D. 2019. People with Low Back Pain Display a Different Distribution of Erector Spinae Activity During a Singular Mono-Planar Lifting Task. Frontiers in Sports and Active Living, 1. **(Appendix 1)**

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Chapter Three

SANDERSON, A., MARTINEZ-VALDES, E., HENEGHAN, N. R., MURILLO, C., RUSHTON, A., FALLA, D. 2019. Variation in the spatial distribution of erector spinae activity during a lumbar endurance task in people with low back pain. J Anat, 234, 532-542. **(Appendix 2)**

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Test-Retest Reliability of Trunk Motor Variability Measured By Large-Array Surface Electromyography

Author: Jacques Abboud,François Nougarou,Michel Loranger,Martin Descarreaux
Publication: Journal of Manipulative and Physiological Therapeutics
Publisher: Elsevier
Date: July–August 2015

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