Spinal kinematic variability in people with chronic low back pain

By

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Abstract

Low back pain (LBP) is one of the leading causes of disability globally and chronic non-specific LBP (CNSLBP) accounts for the vast majority of cases. It is widely acknowledged that people with LBP move differently than pain-free individuals. An abundance of research has examined trunk motor control to understand how movement is controlled in the presence of LBP by evaluating both trunk movement patterns and trunk muscle activity. A commonly observed motor adaptation to spinal pain is a change in spine kinematics, such as angular displacement, angular velocity, as well as changes in the variability of these kinematic variables. However, kinematic variability as a motor adaptation to pain in people with CNSLBP has received less attention and still requires further clarification. This thesis presents research to investigate trunk motor adaptations in people with CNSLBP, specifically, by evaluating kinematic variability differences compared to asymptomatic individuals as a critical element of motor performance during repetitive movements. Additionally, the thesis explores factors such as their trunk muscle co-activation patterns and their clinical characteristics in order to gain insights into possible explanations for different movement variability. The *first study* was a systematic review which confirmed the existence of a different motor pattern in people with CNSLBP, as indicated by differences in spinal kinematic variability compared to asymptomatic individuals during various functional and non-functional repetitive trunk movements. Furthermore, two experimental studies explored the differences in kinematic variability in people with CNSLBP compared to asymptomatic individuals performing two different tasks using the same linear metric to measure variability during repetitive trunk movements. In the *second study* we applied a novel real-time tracking task using a 3D motion capture system to assess trunk motor control. This study did not reveal any differences in movement variability in CNSLBP people when compared with asymptomatic individuals, however, it showed that movement variability over repeated tracking cycles was associated with the degree of fear of movement in

people with CNSLBP. Additionally, the response of those with CNSLBP was consistently delayed in tracking the visual feedback compared to the asymptomatic individuals. The *third study* tested a lifting task reflecting activities of daily living which detected an increase in movement variability in individuals with CNSLBP, despite performing the task within the same spinal range of motion. Moreover, two additional experiments have introduced the novel application of helical axis (HA) parameters as a measure of spinal kinematic variability during repetitive trunk movements. The *fourth study* tested the use of HA parameters on asymptomatic individuals which revealed its sensitivity to changes in movement plane and movement speed. The first application of this measure on people with CNSLBP was in the *fifth study* which revealed an increase in spinal kinematic variability compared to asymptomatic individuals during active trunk repetitive movements, irrespective of the speed or direction of movement. In addition, people with a higher fear of movement showed the lowest kinematic variability. Overall, this thesis further highlights the interaction between physical and psychological features of CNSLBP. The thesis offers new insights into how motor adaptations to spinal pain are present, which suggests the need for tailored interventions to address the unique mechanical presentation of each individual with CNSLBP.

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List of Papers and Conference Abstracts

The following papers directly related to this thesis have either been published, presented at conferences, during the candidate's PhD course, or were under review at the time of thesis submission. A summary of each paper and its use within this thesis will be provided at the start of each relevant chapter. Therefore, sections of this thesis incorporate verbatim text from published work and will resemble this work in terms of structure and content, with additional modifications as required to build the argument of the overall thesis.

Published Articles

Amal M. Alsubaie, Masood Mazaheri, Eduardo Martinez-Valdes, and Deborah Falla. 2021a. Is movement variability altered in people with chronic non-specific low back pain: a protocol for a systematic review, *BMJ Open*, 11(5), p.e046064 **(Appendix 1)**

Amal M. Alsubaie, Masood Mazaheri, Eduardo Martinez-Valdes, and Deborah Falla. 2023a. Is movement variability altered in people with chronic non-specific low back pain? A systematic review, *PLOS ONE*, 18(6), p.e0287029 **(Appendix 2)**

Amal M. Alsubaie, Eduardo Martinez-Valdes, Alessandro Marco De Nunzio, and Deborah Falla. 2021b. Trunk control during repetitive sagittal movements following a real-time tracking task in people with chronic low back pain, *Journal of Electromyography and Kinesiology*, 57, p.102533. **(Appendix 4)**

Amal M. Alsubaie, Andy Sanderson, Hélio V. Cabral, Eduardo Martinez-Valdes, and Deborah Falla. 2023b. Spinal kinematic variability is increased in people with chronic low back pain during a repetitive lifting task, *Journal of Electromyography and Kinesiology*, 73, p.102832. **(Appendix 6)**

Under Review

Amal M. Alsubaie, Corrado Cescon, Eduardo Martinez-Valdes, Marco Barbero, and Deborah Falla. Increased spinal kinematic variability in people with chronic low back pain revealed by alternations in helical axis parameters (*Journal of Biomechanics*)

Conference Presentations (Presenter is highlighted in bold)

Amal M. Alsubaie, **David Jiménez-Grande**, and Alessandro Marco De Nunzio. Trunk coordination in people with low back pain during goal-directed repetitive sagittal trunk movements. The 11th Congress of the European Pain Federation (EFIC). Valencia, Spain, September 4 – 7, 2019.

Amal M. Alsubaie, David Jiménez-Grande, and Alessandro Marco De Nunzio. Trunk coordination in people with low back pain during goal-directed repetitive sagittal trunk movements. Physiotherapy UK conference, The Chartered Society of Physiotherapy. Birmingham, United Kingdom, November 1-2, 2019

Amal M. Alsubaie, Eduardo Martinez-Valdes, Alessandro Marco De Nunzio, and Deborah Falla. Trunk motor control during repetitive sagittal movements following a real-time tracking task in people with chronic low back pain. International Society of Electrophysiology and Kinesiology (ISEK). Virtual Congress, July 12-14, 2020.

Amal M. Alsubaie, Andy Sanderson, Hélio V. Cabral, Eduardo Martinez-Valdes, and Deborah Falla. Spinal kinematic variability is increased in people with chronic low back pain during a repetitive lifting task. UK Sensorimotor Conference. Newcastle, United Kingdom, June 26-28, 2023.

Amal M. Alsubaie, Corrado Cescon, Eduardo Martinez-Valdes, Marco Barbero, and **Deborah Falla.** Methodological analysis of finite helical axis behaviour to assess trunk motor variability during repetitive Movements. International Society of Electrophysiology and Kinesiology (ISEK). Québec City, Canada, June 22 - 25, 2022.

Amal M. Alsubaie, Corrado Cescon, Eduardo Martinez-Valdes, Marco Barbero, and Deborah Falla**.** Methodological analysis of finite helical axis behaviour to assess trunk motor variability during repetitive movements. The 13th Australasian Biomechanics Conference (ABC13). Brisbane, QLD, Australia, November 27 -29, 2022.

Amal M. Alsubaie, Corrado Cescon, Eduardo Martinez-Valdes, Marco Barbero, and Deborah Falla. Estimating trunk kinematic variability via dispersion of the finite helical axes. The Chartered Society of Physiotherapy (CSP) Annual Conference 2023. Birmingham, United Kingdom, November 1, 2023.

Amal M. Alsubaie, Corrado Cescon, Eduardo Martinez-Valdes, Marco Barbero, and Deborah Falla. Spinal kinematic variability is increased in people with chronic low back pain. The Chartered Society of Physiotherapy (CSP) Annual Conference 2023. Birmingham, United Kingdom, November 1, 2023.

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ABBREVIATIONS

Acronym	Definition
2D	Two Dimensional
3D	Three-Dimensional
AA	Angular Acceleration
AD	Angular Displacement
ApEn	Approximate Entropy
ASIS	Anterior Superior Iliac Spines
AV	Angular velocity
BMI	Body Mass Index
CCI	Co-Contraction Index
CI	Confidence Interval
CNS	Central Nervous System
CNSLBP	Chronic Non-Specific Low Back Pain
CON	Controls
CRP	Continuous Relative Phase
CV	Coefficient of Variation
D&B	Downs And Black Scale
DASS-21	Depression, Anxiety and Stress Scale
DET	Determinism
DOFs	Degrees-of-Freedom
DP	Deviation Phased
DRP	Discrete Relative Phase
DST	Dynamical Systems Theory
EMG	Electromyography
EO	Obliquus Externus Abdominis
ES	Lumbar Erector Spinae
FABQ	Fear-Avoidance Beliefs Questionnaire
FHA	Finite Helical Axis
FreBAQ	Fremantle Back Awareness Questionnaire
GRADE	Grading Of Recommendations Assessment, Development, And Evaluation
GRFs	Ground Reaction Forces
HA	Helical Axis
IC	Iliac Crests
IHA	Instantaneous Helical Axis
IMUs	Inertial Measurement Units
IO	Obliquus Internus Abdominis
IPAQ	International Physical Activity Questionnaire
IR	Infrared
LBP	Low Back Pain
LD	Latissimus Dorsi
LES	Lumbar Erector Spinae
LS	Lumbar Segment
LS	Lumbosacral

MA	Mean Angle
MCP	Metacarpophalangeal
MD	Mean Distance
MESH	Medical Subject Headings
MVC	Maximum Voluntary Contraction
NA	Not Applicable
NPRS	Numeric Pain Rating Scale
NR	Not Reported
NRS	Numerical Rating Scale
ODI	Oswestry-Disability-Index
OEA	Obliques Externus Abdominis
OIS	Optimal Information Size
PCS	Pain Catastrophizing Scale
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PSIS	posterior superior iliac spine
RA	Rectus Abdominus
REC	Recurrence
RMDQ	Roland–Morris Disability Questionnaire
ROM	Range of Motion
RPE	Borg Rating of Perceived Exertion
S/speed	Self-Selected Speed
S1-S6	Shelf One- Shelf Six
SaEn	Sample Entropy
SARA	Symmetrical Axis of Rotation Approach
SD	Standard Deviation
SE	Standard Error
sEMG	Surface Electromyography
SF-36	36-Item Short Form Survey
SMD	Standardised Mean Difference
STAI	State-Trait Anxiety Inventory
STROBE	Strengthening the Reporting of Observational studies in Epidemiology
STS	Sit-To-Stand-To-Sit
TES	Thoracic Erector Spinae
TL	Thoracolumbar
TMCf	Time-Varying Multi-Muscle Co-Activation Function
TMJ	Temporomandibular
TS	Thoracic Segment
TSK	Tampa Scale for Kinesiophobia
UCM	Uncontrolled Manifold
Var	Variability
VAS	Visual Analog Scale
λmax	Maximum Lyapunov exponent

CHAPTER 1

GENERAL INTRODUCTION

1.1 Overview of low back pain

1.1.1 Terminology and classifications of low back pain

The lower back is the anatomical region covering the lumbar spine bounded by the bottom of the rib cage and the buttock creases (Savigny et al., 2009). Consequently, low back pain (LBP) is clinically defined as pain, muscle tension, or stiffness localised below the costal margin and above the inferior gluteal folds, with or without referred leg pain (sciatica) (Airaksinen et al., 2006, Koes et al., 2006).

Many clinicians, alongside researchers within the field of LBP, believe that effective treatment is lacking due to the tendency to treat LBP patients as one homogenous condition (Hebert et al., 2011, Petersen et al., 2017). Therefore, numerous approaches have been developed to subgroup patients with LBP (Hebert et al., 2011) in an attempt to improve treatment success. Researchers have focused on identifying subgroups based on diagnostic, prognostic, and treatment-oriented factors (Petersen et al., 2017). The diagnostic triage is a simple and practical classification that has gained international acceptance which classifies LBP into three categories: specific spinal pathology, nerve root pain/radicular pain, and non-specific LBP (Waddell, 1987). Most cases of LBP (85%) are classified as “non-specific”, which means no known specific pathology can be found as a cause (e.g., infection, tumour, osteoporosis, fracture, structural deformity, inflammatory disorder, radicular syndrome, or cauda equina syndrome) (Balagué et al., 2012, O’Sullivan, 2005, van Tulder et al., 2006). The focus of this thesis is on non-specific LBP.

LBP symptoms vary across cases with some lasting a longer duration, making it conventionally categorised according to duration of symptoms, as acute (< 6-weeks), sub-acute (6-weeks – 12-weeks) and chronic (> 12-weeks) (Savigny et al., 2009, Violante et al., 2015). However, most patients with acute LBP recover reasonably quickly compared to 10-15% of patients who will develop chronic symptoms (Balagué et al., 2012). Moreover, a further feature of LBP is high recurrence with 27-87% of cases experiencing repeated episodes of LBP within a year of the first episode (Stanton et al., 2009).

1.1.2 Epidemiology and impact of chronic LBP

Chronic non-specific LBP (CNSLBP) is a challenging clinical condition due to various contributing factors including its high prevalence and impact on quality of life. LBP is the main cause of years lived with disability (Ferreira et al., 2023, Hartvigsen et al., 2018, Wu et al., 2020), and the leading cause of activity limitation and absenteeism from work (Lee et al., 2015). Further, it has diagnostic and interventional challenges reported by clinicians and researchers (Bonfim et al., 2021, Delitto et al., 2012), as well as high economic burden even on high income countries (Fatoye et al., 2023).

In the year 2020, there were more than half a billion cases of LBP reported worldwide, yet, projections indicate that by the year 2050, the global prevalence of LBP is expected to exceed 800 million individuals (Ferreira et al., 2023). The prevalence rate of CNSLBP differed from that of chronic specific LBP, with rates of 15.4% and 9.3%, respectively (Iizuka et al., 2017). In addition, it is estimated that 15% to 20% of adults will experience LBP during a single year and 50% to 80% will experience at least one episode of LBP during a lifetime (Rubin, 2007). Further, there is an evidence suggests that the prevalence or incidence of LBP tends to increase with age (Jeffries et al.,

2007). The anticipated substantial rise as the population ages over the coming decades will particularly affect individuals between the ages of 40 and 80 years old, especially females (Hoy et al., 2012).

Chronic LBP has commonly been associated with manual material handling (Violante et al., 2015) which contributed to the higher incidence of chronic LBP among occupational workers across different industries (Jia et al., 2022, Wami et al., 2019). Furthermore, various factors were identified as risk factors for LBP development including: engaging in frequent trunk repetitive movements, working at a high pace in the same position, frequent trunk twisting or turning movements, working overtime, lifting heavy loads, education level, working age, use of vibration tools at work as well as anthropometric factors, and habits such as cigarette smoking (Jia et al., 2022). One hypothesis to be explored in this thesis is whether the accumulation of spinal loads from different-paced repetitive trunk movements, whether fast or slow, can impact the movement behaviour of individuals with CNSLBP.

1.2 Understanding spinal movement

1.2.1 Basic anatomy of the spine

The spine is a complex system which plays a vital role in maintaining posture and facilitating movements of the head and trunk while also providing protection to the spinal cord and nerve roots (Izzo et al., 2013). The vertebral column consists of the vertebrae of the cervical, thoracic, lumbar, sacral, and coccygeal regions along with the intervertebral discs, ligaments, rib cage, and spinal musculature (Oxland, 2016).

When studying the movement of the spine, a global anatomical view is taken to understand its overall functionality, rather than a local view of a component such as the annulus fibrosus of the

intervertebral disc (Oxland, 2016). When viewing the spine from the frontal plane, it exhibits a straight appearance, whereas it has an S-shape from the sagittal plane (**Figure 1.1)** (Galbusera and Wilke, 2018). Three spinal regions are defined based on the sagittal curvatures; cervical spine which connects the head and trunk, normally exhibiting a lordotic curvature (i.e., a concavity in the dorsal direction) when standing, the thoracic spine that supports the rib cage and features a kyphotic curvature (i.e., a ventral concavity), the lumbar spine which connects the trunk to the pelvis and displays a lordotic curvature, and additionally the sacral bone, comprising several fused vertebrae that connects the lumbar spine and the pelvis (Galbusera and Wilke, 2018).

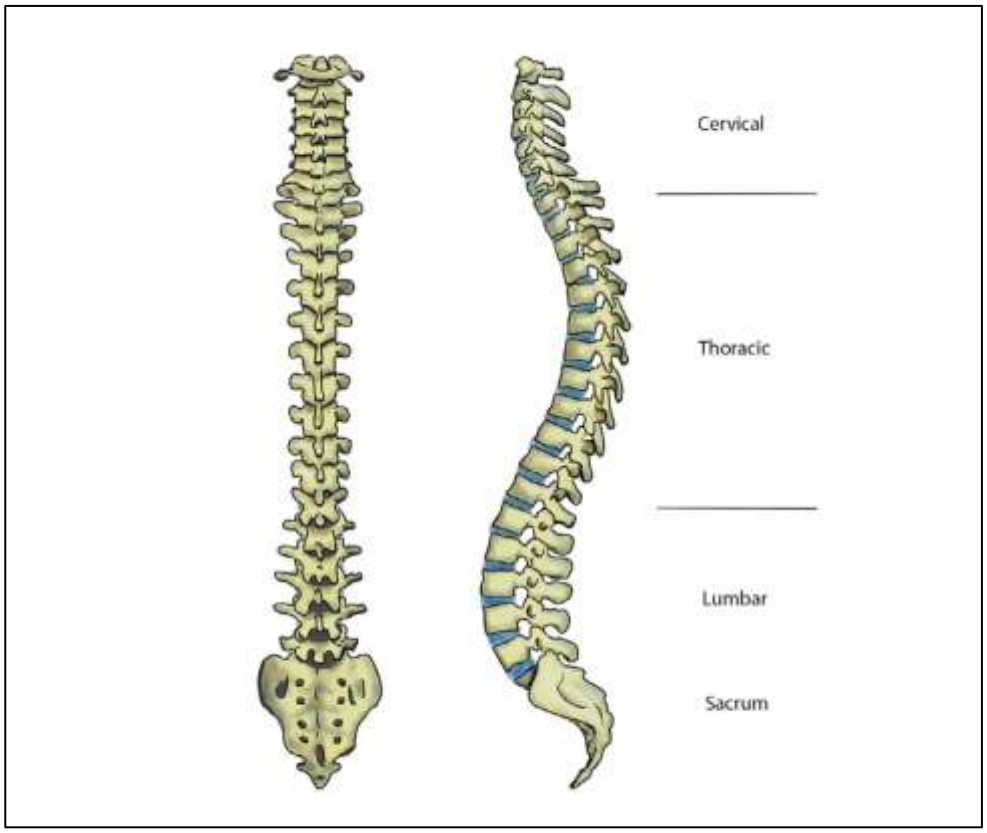


Figure 1.1: **The three spinal regions defined from the sagittal view (right) in addition to the frontal view (left)**

From Galbusera, F. and Wilke, H.J. eds., 2018. Biomechanics of the spine: Basic concepts, spinal disorders and treatments. Academic Press.

Apart from the main function of the spinal column to protect the nervous structures, spinal stability is a basic functional requirement to transfer forces between the upper and lower limbs, generate active forces in the trunk, prevent early deterioration of the structural elements of the spine as well as to reduce energy expenditure during muscle action (Izzo et al., 2013). To generate physical movements, trunk local and global muscles work together, as described by Bergmark (1989) based on their structural characteristics. Local muscles are thought to be responsible for the segmental control and stability of the spine and are located deep in the trunk; this includes the transversus abdominis and multifidus (Mitsuda and Nakajima, 2023). On the other hand, global muscles are located superficially and generate torque around the spinal column; this includes rectus abdominis, external oblique, erector spinae, and iliopsoas muscles. In physical movements, these local and global muscles work together (Mitsuda and Nakajima, 2023).

1.2.2 Functional biomechanics of the spine

The biomechanics of human movement can be defined as the interdisciplinary study that describes, analyses, and assesses diverse movements with the same physical and biological principles applied; covering a wide range of activities, from examining gait patterns of individuals with disabilities to studying the mechanics of lifting a load in industrial settings as well as investigating the performance of elite athletes (Winter, 2009). The main function of the spine in protecting the neural elements is added to the biomechanical goals to enable trunk movements while providing structural support (Oxland, 2016).

In an attempt to connect the passive osteo-ligamentous structures of the spine with the active neuromuscular system; the Spine Stabilising System hypothesis proposed that the complex neuromuscular system is responsible for keeping the human spine mechanically stable at all times to

avoid injury that may leads to pain (Panjabi, 1992a, Panjabi, 1992b). Spinal stability has been defined as the spine's ability to withstand physiological loads with limited patterns of displacement in order not to damage or irritate the spinal cord and nerve roots and to prevent incapacitating deformity or pain caused by structural changes (White et al., 1975). This clear definition of stability was an important benchmark, yet it remains difficult to apply clinically (Oxland, 2016). Employing a precise engineering term in clinical contexts poses a challenge when subjective parameters such as pain and function are the prominent outcomes (Oxland, 2016). Similarly, the American Academy of Orthopedic Surgeons defined stability as "the capacity of the vertebrae to remain cohesive and to preserve the normal displacements in all physiological body movements" (Kirkaldy-Willis and Farfan, 1982). However, in order to identify a spinal movement as abnormal, it is necessary to presuppose an understanding of what is considered normal (McGregor et al., 1997). Defining a "normal or physiological spinal movement" remains a matter of debate (Izzo et al., 2013).

Segmental spinal motion involves two adjacent vertebrae with interposing soft tissues; each vertebra has the capability to perform three translations along and three rotational movements around each of the x-y-z-Cartesian axes in space (Izzo et al., 2013). This is referred to as arthrokinematics or accessory passive movements between spinal joints, however, because impairments in accessory motion cannot be observed clinically, osteokinematics or gross active physiological movement of the spine is typically considered as part of the assessment and intervention (Sahrmann, 2010, Sahrmann et al., 2017). The lumbar and thoracic regions of the spine can perform various combinations of the main or coupled physiological movements including flexion, extension, lateral flexion and rotation (Izzo et al., 2013, Lawrence et al., 2006).

Although the study of biomechanics primarily involves the mechanics and biophysics of the musculoskeletal system, it's also important to identify its interaction with other areas of movement science such as neurophysiology and anatomy (Winter, 2009). Therefore, variables that are used in

the description and analysis of any human movement including spinal movements can be categorised as follows: kinematics, kinetics, anthropometry, muscle mechanics, and also involving the neural system but only limited to electromyography (EMG) (Winter, 2009). Kinematic variables describe human movement, regardless of the forces that caused that movement which include linear and angular displacements, velocities, and accelerations (Winter, 2009). In general, kinematic analysis provides information about the strategy or movement pattern employed by an individual to execute a motion or a task (Li et al., 2021). Therefore, knowledge of spinal kinematics, through distinguishing between physiological and pathological motion patterns, is essential for the assessment and management of various spinal conditions (Lindenmann et al., 2022). In addition, since movement cannot be separated from its neural control, EMG data serves as the final control signal of each muscle generated during its contraction, representing a measure of neuromuscular activity (Garza-Ulloa, 2018, Winter, 2009).

1.2.3 Kinematic measurement systems

Over many decades, methods for kinematic measurement have been developed and utilised in the field of biomechanics (Stančić and Zanchi, 2008). Several technologies are employed for kinematic measurement, depending on the particular application and specific requirements. For instance, two dimensional (2D) analysis can provide a quick and effective method of evaluation in activities such as walking or running that needs to be analysed in the sagittal plane mainly (Roggio et al., 2021). However, if the movement necessitates the analysis on multiple planes or involves the investigation of forces, it is more suitable to use a three-dimensional (3D) system, which requires a higher level of expertise (Roggio et al., 2021).

Motion capture systems are used to acquire 3D kinematics of the human body (including position, velocity, and acceleration) enabling researchers and clinicians to evaluate the functional motor capabilities of individuals and identify impairments in movement patterns (Arslan et al., 2019). Furthermore, motion analysis serves multiple purposes, including guiding rehabilitation protocols, evaluating the efficacy of orthotics, prosthetics, or exoskeletons, and quantitatively assessing sports injury risks in a reliable manner (Arslan et al., 2019).

Optoelectronic motion capture systems are reliable and suitable methods to measure complex high-speed movements and are often considered as the gold standard in motion capture, providing high accuracy in both static and dynamic measurements (Sessa, Zecca et al. 2013, Colyer, Evans et al. 2018, van der Kruk and Reijne 2018). Frequently, the traditional motion analysis systems consist of multiple cameras that perceive the positions of reflective markers and a force platform that have a capability of measuring kinetic data (e.g., ground reaction forces; GRFs) (**Figure 1.2**) (Arslan et al., 2019, Garza-Ulloa, 2018). Moreover, by incorporating EMG recordings, it is also possible to gain insight into the activation levels of muscles during movement (Arslan et al., 2019). The focus in this thesis will be directed towards analysing patterns of trunk muscle co-activation aiming to see how these muscles work synergistically to maintain posture, stabilise the spine, and execute various trunk movements. This not only provides valuable information about trunk motor control but also sheds light on potential dysfunctions or imbalances that may contribute to LBP. Co-activation indexes have the advantage of facilitating inter-group comparisons, allowing researchers to assess muscle activity levels across individuals or groups with diverse physical characteristics. Nevertheless, these indexes are sensitive to normalisation methods, particularly in tasks involving cyclic and repetitive trunk movements, which can pose challenges, potentially leading to variability in results and interpretation across studies (Ghazwan et al., 2017). In this thesis, appropriate

normalisation techniques will be selected considering the nature of tasks involving cyclic and repetitive trunk movements.

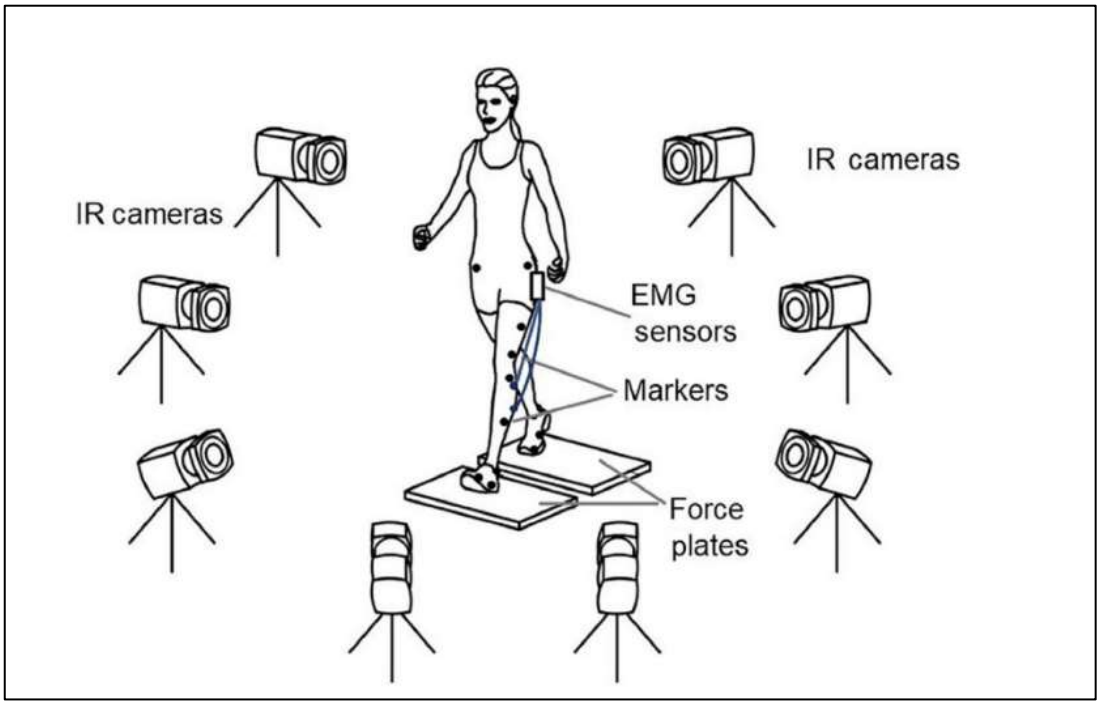


Figure 1.2: **Traditional motion analysis system including infrared (IR) cameras, reflective markers, EMG recording system, and force plates**

From Arslan, Y.Z., Karabulut, D., Ortes, F. and Popovic, M.B., 2019. Exoskeletons, exomusculatures, exosuits: dynamic modeling and simulation. Biomechatronics, Elsevier, pp.305-331.

Reflective markers are used on specific anatomical landmarks to track the motion or movement patterns of that labelled body segment with the data recorded at a series of time intervals (Arslan et al., 2019, Garza-Ulloa, 2018). In order to achieve that, at least three markers are required to define the spatial location of each body segment (Arslan et al., 2019, Garza-Ulloa, 2018). The markers' placement protocol must be simple, yet thorough enough to accurately define the relative motion of the body segments (Kadaba et al., 1990).

To capture the movement of each body segment in the sagittal, frontal, and transverse planes, it is necessary for the 3D positions of markers to remain visible to at least two cameras throughout the recording process (Garza-Ulloa, 2018). However, in cases where this requirement is not met on short sections of the recording, modern motion analysis resources often provide interpolation tools to fill in the missing data by estimating the position from earlier and later frames using mathematical algorithms (Arslan et al., 2019, Garza-Ulloa, 2018).

Optoelectronic motion capture systems provide an objective, quantitative, and reliable data to assess spine posture and motion, especially for the use in clinical settings (Mousavi et al., 2018). They have been used to evaluate spinal range of motion (ROM), such as quantifying lumbar flexion-extension, lateral flexion, and axial rotation as well as evaluating static and dynamic postural changes during activities such as sitting, standing, walking, or running (Pourahmadi et al., 2019, Suter et al., 2020).

1.3 Motor control of human movement

Human movement control is a complex process involves hundreds of muscles working together to move various joints, resulting in smooth and accurate movement effortlessly, even under consistently changing demands (Bastian, 2008). These active voluntary movements are self-generating actions initiated as a result of cognitive processes (Virameteekul and Bhidayasiri, 2022).

The central nervous system (CNS) selects potential muscle activation patterns from a theoretical set of solutions within the available mechanical degrees-of-freedom (DOFs), featuring the issue of redundancy at the neural level of the neuromuscular system (Bernstein, 1967). However, the positive aspect of this redundancy is that it allows the neuromuscular system to be very adaptable

(Winter, 1984). This is thought to be critical for motor flexibility, specifically, motor adaptation and motor learning (Bastian, 2008).

Motor adaptation, according to Martin et al. (1996), is modification in the movement pattern from trial-to-trial which occurs gradually overtime with repetition, and once adapted, it's not possible to retrieve the prior behaviour and de-adaption is required through practice in the same gradual, and continuous manner back to the original state (Bastian, 2008, Martin et al., 1996). Motor learning, on the other hand, is referred to the formation of a new movement pattern through long-term practice, and in contrast to motor adaptation, the new acquired movement pattern is stored and can be brought up and used within the appropriate context with the ability to efficiently switch from one learned motor pattern to another (Bastian, 2008). However, both motor adaptation and learning are fundamental processes to refine movement patterns and improve skills, especially in activities of daily living that involve repetitive functional movements (Kitago and Krakauer, 2013).

1.3.1 Movement adaptations in chronic LBP

In the presence of LBP, people often move differently compared to those without pain (Hodges and Tucker, 2011, van Dieën et al., 2019b). The observed movement changes have been attributed to several motor adaptations (i.e., neuromuscular) found in people with spinal pain such as greater muscle co-contraction, re-distribution of muscle activity, delayed postural control of trunk muscles, as well as reduced spinal ROM (Devecchi et al., 2021). In individuals with chronic LBP specifically, motor adaptations include reduced lumbar ROM in all movement directions, slower motion, and reduced proprioception when compared to those without LBP (Laird et al., 2014). However, it remains unclear whether reduced proprioception is a motor adaptation as a result of

CNSLBP or if it serves as a compensatory mechanism for the altered proprioception and changes in central sensory processing (Laird et al., 2014). Nevertheless, it is anticipated that any proprioceptive impairment associated with LBP will affect the precise control of trunk movement and could potentially lead to poorer quality of movement (Lee et al., 2010, Willigenburg et al., 2013). Proprioceptive deficiencies are often evaluated while performing tracking or aiming tasks, which are suggested to highlight these deficiencies more evidently (Willigenburg et al., 2013). Another method that will be utilised within this thesis to assess trunk motor control involves providing a visual feedback and measuring the temporal difference between the feedback movement and actual trunk motion.

Adaptations in kinematic parameters in the presence of LBP have been identified during various common daily activities. During walking, for instance, people with chronic LBP walk more slowly and take smaller steps with altered patterns of coordination between the trunk and pelvis compared to individuals without LBP (Smith et al., 2022). Similarly, LBP influences trunk kinematics during sit-to-stand-to-sit movements, as people with chronic LBP present with decreased lumbar ROM, slower velocity of displacement, decreased acceleration, and greater kinematic variability of the trunk (Sedrez et al., 2019).

However, the mechanisms behind these motor control changes in people with chronic LBP are poorly understood (van Dieën et al., 2019b). Therefore, researchers have recently proposed several theories in an attempt to explain the clinical and experimental observations in people with chronic LBP as well as translating it into clinical interventions for the management of their LBP (Hodges and Tucker, 2011, Hodges et al., 2013, van Dieën et al., 2019b). One of the proposed theories has reported that that the affected motor control in people with chronic LBP is in order to protect the tissues from further pain or injury, by changing the pattern of activity of trunk muscles, mechanical behaviours, as well as reducing responsiveness to sensory input (Hodges and Tucker, 2011).

Moreover, pain and/or pain-related fear can alter trunk motor variability and stability as components of motor adaptations toward chronic LBP (Hodges and Tucker, 2011).

While the biological and psychological domains are commonly discussed separately, it is likely that they are interconnected (Karayannis et al., 2013). Therefore, understanding how the biological and psychological factors interact is crucial, as they both affect the presentation and management of LBP which is a hypothesis to be tested in this thesis. Motor control such as trunk motor variability, and psychological factors like fear of movement and disability level, are expected to impact motor output and trunk mechanics.

1.3.2 Motor variability

Motor variability is easily observable in all biological systems, for example, when repeating the same trunk movement twice, the two actions will never be identical (Stergiou and Decker, 2011). It also reflects the natural variations that occur in motor performance across multiple task repetitions (Stergiou et al., 2006). Trunk motor stability refers to the dynamic ability of the trunk to offset an external perturbation and return to the same position (Latash and Huang, 2015, Stergiou and Decker, 2011). Hence, motor variability and motor stability are two different components within the motor control process (Stergiou and Decker, 2011). The ability to generate precise and appropriate motor behaviour relies on adjusting motor commands to match the current movement context (Wolpert and Ghahramani, 2000). However, when talking about execution of trunk movements, there is still lack of clear consensus on the optimal levels of motor variability and stability necessary to achieve coordinated movements without compromising the spine's integrity, particularly during dynamic and repetitive activities (Cowin et al., 2022). This concept of optimal control of movement has been proposed based on maximising movement smoothness, however, it is still unclear why

smoothness is important and how it is measured by the CNS (Wolpert and Ghahramani, 2000). In light of these considerations, this thesis will concentrate on the paradigm of movement variability offering insights into the adaptability of the motor control system. It will also clarify some of the differences between movement variability and movement stability.

Some of the prominent theories that have considered variability in motor performance include the Generalised Motor Program Theory, which considers variation in a given movement pattern as a result of an error (Summers and Anson, 2009). The hypothesis of the Uncontrolled Manifold (UCM) proposes that there are several potential solutions available for a given motor problem (Scholz and Schöner, 1999). A third theoretical perspective is the Dynamical Systems Theory (DST) that introduces the biological system as a self-organising system according to the environmental, biomechanical, and morphological constraints to produce the most stable movement (Kamm et al., 1990). In the past, motor variability was typically believed to be a random error or noise (Holden, 1988). However, by now it is well recognised that motor variability is not simply a reflection of random noise, instead, it reveals hidden features and regulations which provides valuable insights into both healthy and pathological motor control (Abboud et al., 2014, Lamoth et al., 2006a).

Most of the past perspectives on motor variability are similar in recognising that a decrease in variability indicates a highly stable behaviour that results from an efficient execution of a given movement pattern (Stergiou and Decker, 2011). However, this general idea is closely related to the context of motor learning in skill acquisition rather than motor adaptation, for instant in sports tasks where consistency is necessary to achieve a desired result across repetitions (Ranganathan et al., 2020, Stergiou and Decker, 2011). On the contrary, increased variability could also be considered as a beneficial component for motor performance, for instance it can prevent low back injury by re-distributing joint loads during repetitive trunk motions (Nordin and Dufek, 2019). In this situation, low variability may lead to repeated strain applied to the same body structure, which could result in

increased risk of overuse injury (James, 2004). Moving with excessively high variability, on the other hand, may also be associated with unexpected changes and unfamiliar movements that is prone to injury (Cowin et al., 2022, Stergiou et al., 2006).

A zone has been proposed between too little variability and too much variability as the optimal movement variability following an inverted-U shape (**Figure 1.3**) (Stergiou and Decker, 2011, Stergiou et al., 2006) . The optimal zone of movement variability falls between excessive maximum predictability of the movement and no predictability (Stergiou and Decker, 2011). Thus, loss of this optimal movement variability will either lead to more predictable, rigid and robotic type of movement behaviour or toward extremely unpredictable movement patterns (Stergiou and Decker, 2011).

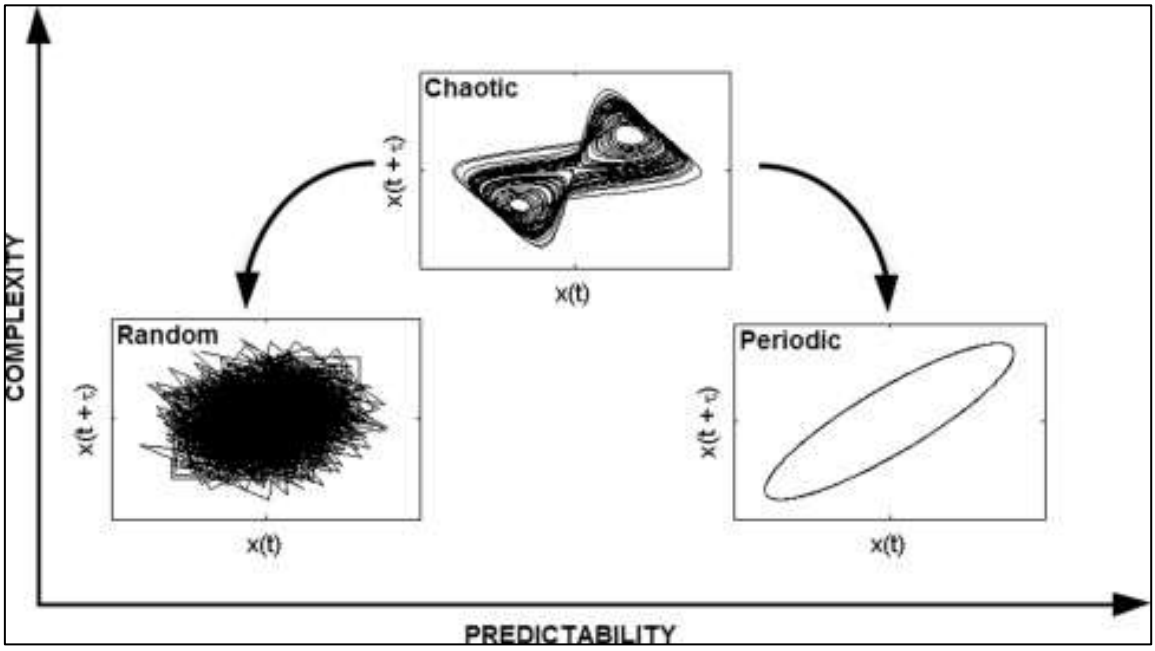


Figure 1.3: **Theoretical model of optimal movement variability illustrated using three signals ("Periodic", "Chaotic", and "Random").**

From: Stergiou, N. and Decker, L.M., 2011. Human movement variability, nonlinear dynamics, and pathology: is there a connection?. Human movement science, 30(5), pp.869-888.

1.4 Methods for evaluating movement variability

Most of the existing controversies in the literature concerning human movement variability are mainly attributed to the different methodologies used (Stergiou and Decker, 2011). Linear and non-linear measurement tools were designed to quantify the amount and structure of motor variability, respectively (Harbourne and Stergiou, 2009, Komar et al., 2015, Krüger et al., 2017). These two approaches are complimentary to explore two different aspects of variability (**Figure 1.4**) (Harbourne and Stergiou, 2009, Katsavelis et al., 2010, Stergiou et al., 2004).

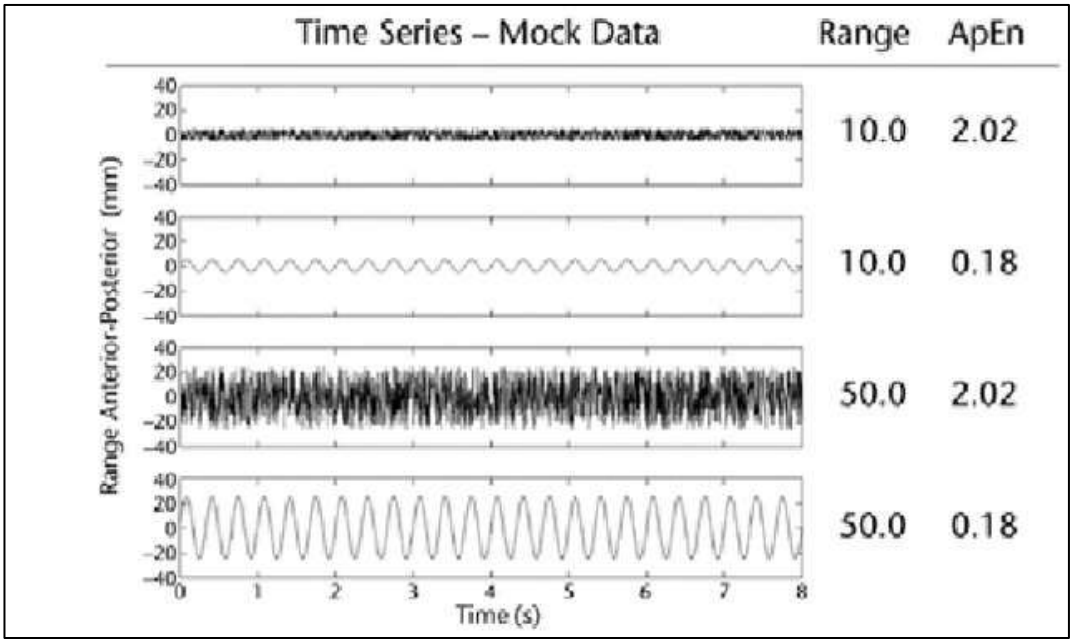


Figure 1.4: **Complementary linear and nonlinear measures from several signals.** Four signals are displayed, with the respective values for range and approximate entropy (ApEn). Which shows that different amounts of variation does not necessitate a change in the structure of variability of a data series. From: Katsavelis, D., Mukherjee, M., Decker, L. and Stergiou, N., 2010. The effect of virtual reality on gait variability. Nonlinear Dynamics, Psychology, and Life Sciences, 14(3), pp.239-256.

1.4.1 Linear measures

The conventional linear statistical tools such as range, standard deviation (SD), and coefficient of variation, are measures of centrality and thus quantify the magnitude or the amount of variation regardless of the signals order in the distribution (Stergiou and Decker, 2011). SD is the most commonly used measure of dispersion or spread of data about the mean, especially when data distribution is symmetric with no outliers (Manikandan, 2011). The SD is a highly useful measure of variability, due to its inclusive nature, considering all data points in the calculation, it also provides information about the average or standard distance of each score from the mean of the distribution (King and Eckersley, 2019). In spinal motion, for example, when calculating lumbar angles for each repetition of a trunk repetitive task, the linear measure of variability in spinal movement is commonly determined by calculating the average of standard deviations across all cycles, referred to as MeanSD (Asgari et al., 2015, Wildenbeest et al., 2022). This metric will be used more frequently within this thesis due to its established relevance and widespread adoption in analysing spinal motion variability. In addition, it is simplicity in interpretation makes it easier to communicate and facilitates the comparison of results within this thesis and with existing literature, enhancing the coherence and comprehensibility of the research findings.

Moreover, the amount of variability in coordination between two spinal segments has been previously assessed by applying certain techniques, including Discrete Relative Phase (DRP), Continuous Relative Phase (CRP), as well as other methods such as cross-correlations, and root mean squared differences (Ebrahimi et al., 2017, Fujii et al., 2022, Glazier, 2006, Lamoth et al., 2006a, Lamoth et al., 2006b, Seay et al., 2011).

1.4.2 Non-linear measures

In contrast, nonlinear dynamics quantify the structure of variability considering the complexity and the temporal sequence in a series of values (Stergiou et al., 2006). Mathematical tools, such as entropic or fractal measures, as well as tools specifically designed for studying deterministic chaos, have facilitated the assessment of the temporal structure of variability (Stergiou and Decker, 2011). These are considered better in capturing variation of how motor behaviour emerges in time (Stergiou and Decker, 2011). Non-linear measures often associated with terms like "non-linear dynamics" which refers to systems exhibiting complexity and unpredictability compared to linear measures (Harbourne and Stergiou, 2009). This allows for a more comprehensive understanding of performance, particularly when used as a complementary tool with the linear measures in clinical practice (Dierick et al., 2021, Harbourne and Stergiou, 2009).

Largest Lyapunov exponent and sample entropy are some of the tools that have been used in the literature for this purpose along with other nonlinear mathematical tools (Liao et al., 2008, Yang and Wu, 2011). With respect to the assessment of spinal motion, the Lyapunov exponent is recognised as a measure of local dynamic spine stability and correlates with mechanical spine stiffness (Graham et al., 2012). It has proven effectiveness in detecting differences in people with LBP during various daily living activities, including repeated lifting and forward bending and backward return tasks (Asgari et al., 2015, Bauer et al., 2017, Bauer et al., 2015, Dideriksen et al., 2014).

Nonlinear analysis is predominantly used within research settings due to its reliance on mathematical equations and specialised software for evaluation, however, the complexity of movement analysis, with its lengthy time series, poses significant limitations for clinical applications (Harbourne and Stergiou, 2009). Nevertheless, it is important to acknowledge that there is ample information available on how to use non-linear measures, for instance, open-source algorithms that can further facilitate their implementation, mitigating some of the barriers to their

clinical use (Flood and Grimm, 2021, Mehdizadeh, 2019). However, despite these resources, the lack of understanding of the technique itself remains a significant challenge (Harbourne and Stergiou, 2009). Thus, while non-linear measures may pose challenges, their effectiveness in clinical applications can be enhanced through clear guidance on their appropriate use and the availability of accessible tools for implementation.

There is a lack of information in order to determine the optimal tool for assessing spinal movement variability due to the variations in the concepts underlying each analysis technique. However, it has been suggested that linear measures provide higher sensitivity in comparing the spinal movement variability of individuals with and without LBP (Saito et al., 2021). Moreover, linear methods are favoured because of their simplicity, ease of use, and interpretation compared to the nonlinear methods (Schumacher, 2004), making them particularly well-suited for the analytical approach employed in this thesis.

1.4.3 Helical axis

ROM with Euler angles or other angular representations are most commonly used to examine joint kinematics, yet other techniques, such as the finite helical axis (FHA), may allow to detect pathological 3D spine motion more effectively (Ancillao, 2022, McLachlin et al., 2016). FHA methods provide more detailed, less constrained (6- DOFs), and time–dependent representations of joint kinematics, when compared with other approaches for the estimation of functional joint axes (i.e. symmetrical axis of rotation approach (SARA), instantaneous helical axis (IHA)) (Ancillao, 2022, De Benedictis, 2022). In addition, the analysis of the HA defines the movement of two segments by reducing it into a rotation about and translation along a single axis, which allows the evaluation of joint movement variability (Alsultan et al., 2019, Cripton et al., 2001, Grip and Häger, 2013, Grip et al., 2015). Applying HA analysis on the spine, with its multiple joints, provides

additional information compared to the traditional linear measures of variability through capturing the complex, 3D nature of spinal motion and allow for more comprehensive understanding of spinal movement variability.

Recently, the behaviour of HA has been studied in vivo on several joints such as the knee joint (Grip and Häger, 2013, Grip et al., 2015, Grip et al., 2019, Konda et al., 2019, Markström et al., 2020, Temporiti et al., 2020), shoulder joint (Temporiti et al., 2019), temporomandibular joint (TMJ) (Gallo et al., 1997, Gallo et al., 2006), and metacarpophalangeal (MCP) joint (Fioretti et al., 1990). The HA has also been studied in vitro on cadaveric elbows (Muriuki et al., 2012).

The behaviour of HA during spinal movements has never been applied in vivo to investigate the thoracic nor lumbar spine, however, it has only been used in vitro and in simulation studies (Ellingson and Nuckley, 2015, Metzger et al., 2010, Rockenfeller et al., 2021, Schmidt et al., 2008, Wachowski et al., 2009). In contrast, the behaviour of HA during spinal movements has been applied extensively to investigate cervical spine movement **(Figure 1.5)** (Alsultan et al., 2019, Barbero et al., 2017, Cattrysse et al., 2020, Cescon et al., 2014, Dugailly et al., 2015, Ellingson et al., 2013, Grip et al., 2008, Woltring et al., 1994). The reliability of HA measures during active movements of the cervical spine was found to be almost perfect indicating potential descriptors for kinematic variability for evaluating neck function (Barbero et al., 2017). This approach has also proven to be sensitive in detecting changes in kinematic variability as an adaptive strategy to chronic neck pain (Alsultan et al., 2019, Alsultan et al., 2020). Therefore, the HA could be a promising tool to identify differences in spinal kinematic variability in people with LBP. This could be achieved by employing the proposed parameters of HA that were found to be sensitive to both the position and orientation of spinal movement (Barbero et al., 2017). To quantify the suggested parameters, mean distance (MD) and mean angle (MA), the angle of a body segment relative to it is initial position will be calculated for each time frame. This angle, determined using the HA

technique, represents the rotation angle needed to move the body segment from it is initial position (F_0) to its current position at frame (F_i). Once the group of helical axes (i.e. FHA) are computed for all movement cycles, a perpendicular plane will be defined, with the group of helical axes represented as intersection points on the plane, as illustrated in **Figure 1.5**. (Cescon et al., 2019, Cescon et al., 2014).

In light of this explanation, while there is insufficient research for complete validation, the HA could offer further insights into the structure of variability, especially when analysing variability in time-dependent representations of joint kinematics, which consider the temporal aspect. While offering insight into the structure of variability, the HA analysis retains a straightforward interpretation as the linear measures with higher values of MA and MD indicating increased variability, while lower values indicate the opposite.

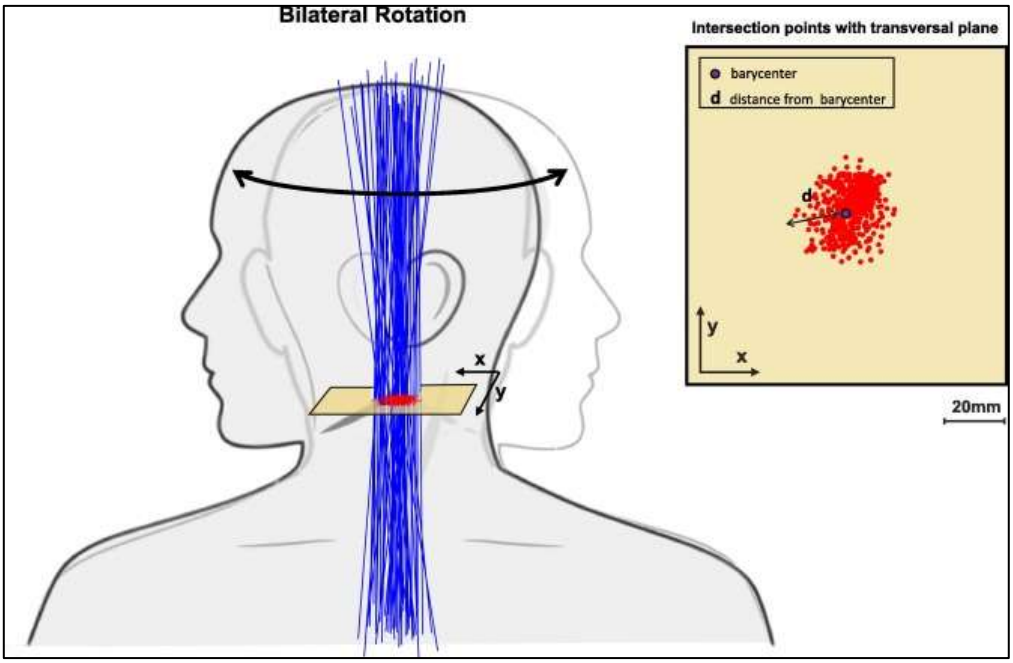


Figure 1.5: **Quantifying the mean distance (MD) and mean angle (MA) of the helical axis parameters**

MD is the intersection points represented in red, MA is the angles of axis lines shown in blue. From: Alsultan, F., Cescon, C., Heneghan, N.R., Rushton, A., Barbero, M. and Falla, D., 2020. Eccentric exercise and delayed onset muscle soreness reduce the variability of active cervical movements. Journal of biomechanics, 111, p.109962.

1.5 Spinal kinematic variability in people with chronic LBP

The mechanical presentation of a given movement, as an altered movement behaviour, has been frequently used to differentiate individuals with LBP from pain-free individuals (Cholewicki et al., 2019). Any changes or redistribution of activity within and between muscles will alter the mechanical outcome of that contraction (Hodges and Tucker, 2011), which, if sustained, may lead to increased spinal loading and potentially degeneration of intervertebral discs and other tissues **(Figure 1.6)** (van Dieën et al., 2017, van Dieën et al., 2019b). Movement variability based on current scientific evidence is believed to be different in people with chronic musculoskeletal disorders compared to healthy individuals (Abboud et al., 2014, Srinivasan and Mathiassen, 2012).

Specifically, considering the anatomical and functional complexity of the lumbar spine, differences in movement variability is anticipated as a motor adaptation to the presence of LBP in order to prevent, delay or alleviate muscle fatigue and the risk of potential musculoskeletal disorders and injuries (Abboud et al., 2014).

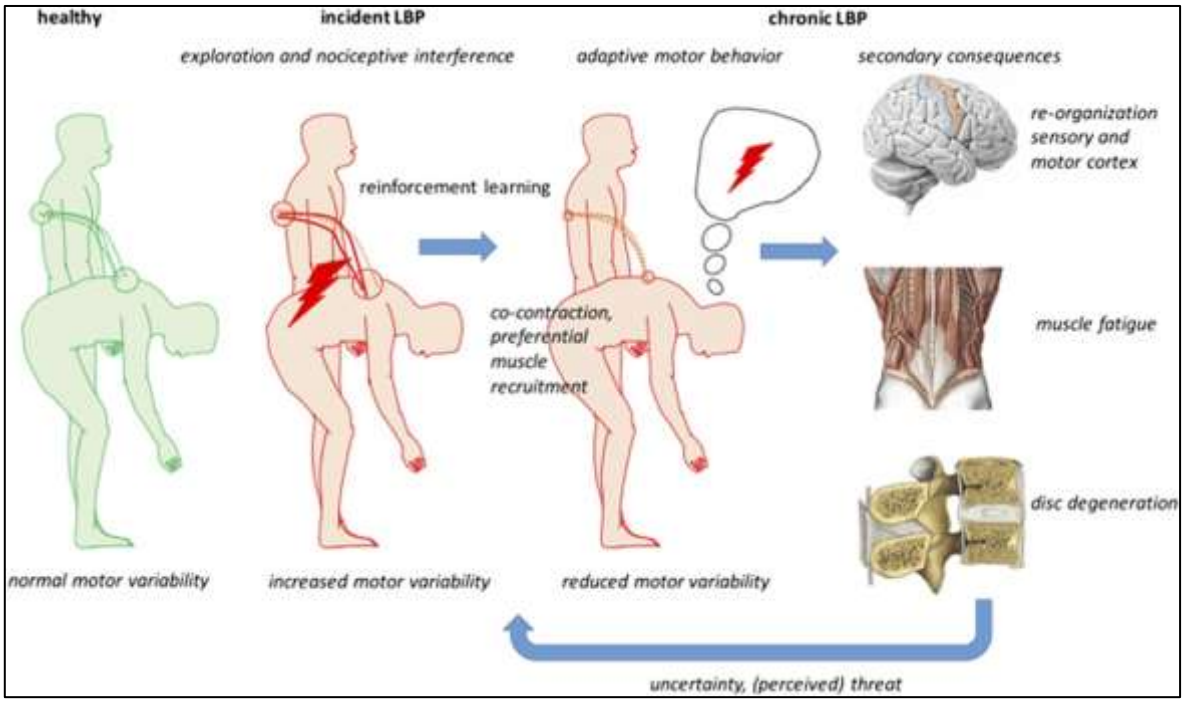


Figure 1.6: **Schematic illustration from a hypothesis on motor control changes with low-back pain (LBP)**

The dotted lines representing the movement trajectories of a marker on the trunk and the circles representing the area of end point positions of this marker over a series of repeated movements. From: van Dieën, J.H., Flor, H. and Hodges, P.W., 2017. Low-back pain patients learn to adapt motor behavior with adverse secondary consequences. Exercise and sport sciences reviews, 45(4), pp.223-229.

Spinal segmental motion can be assessed by a variety of systems that allow for kinematic variables to be measured including intervertebral range of motion, anterior/posterior translation, and proportional motion pattern variability (Cholewicki et al., 2019). Investigating trunk kinematics

during gait revealed reduced trunk movement variability in people with chronic LBP in comparison to an asymptomatic control group (van den Hoorn et al., 2012). However, researchers have also observed the opposite pattern, where individuals with chronic LBP exhibit higher trunk kinematic variability during gait (Vogt et al., 2001), as well as during a standing repeated reach task independent of changes in segmental ROM (Silfies et al., 2009). Despite the similarity in the tasks being studied by van den Hoorn et al. (2012), Vogt et al. (2001), the discrepancies in their findings could be attributed to several factors, including differences in study populations, methodologies, and measurement approaches. One potential explanation could be the different reference frames utilised. While Van den Hoorn et al. (2012) opted for the pelvis frame as their reference frame for analysing trunk kinematics during gait, Vogt et al. (2001) employed the global frame. Therefore, understanding the role of trunk muscles and sensory information processing operated in an anatomical frame, and their effects on variability in the global frame, is essential for expressing and interpreting movement variability assessed with each reference frame.

In addition, the same pattern of increased kinematic variability was observed during a repetitive lifting task in people with chronic LBP (Bauer et al., 2015). The same response was also observed during early phases of a repetitive lifting task in asymptomatic individuals (Tetteh and Mirka, 2021), which indicates that fatigue may have a similar response as observed with the presence of pain (Srinivasan and Mathiassen, 2012).

Optimal kinematic variability is an important characteristic of healthy functioning in human movement (Harbourne and Stergiou, 2009). In the literature, differences in spinal kinematic variability in the presence of LBP have yielded relatively inconsistent findings even though there is a growing body of research focused on kinematic variability during the execution of different activities of daily living. It remains uncertain whether LBP leads to an increase, decrease, or no significant differences in spinal kinematic variability compared to individuals free of back pain.

Despite this inconsistency, it is believed that the differences in spinal kinematic variability among individuals with chronic LBP is an adaptive response to pain rather than being a causative factor for pain (Gallagher et al., 2011, Meier et al., 2019).

The uncertainty on the exact direction of difference in people with LBP compared to asymptomatic individuals necessitates the need for more comprehensive investigations to understand the nature of difference in spinal movement variability. This will not only help in confirming the existing hypotheses but will also contribute to the development of targeted interventions for LBP management. Understanding the unique motor control challenges in individuals with chronic LBP will offer more precise guidance on the most effective type of intervention to improve movement control. This, in turn, may enhance the overall management approach in chronic LBP and improve the quality of life for individuals affected by this condition.

1.6 Thesis aims and objectives

The primary aim of this thesis was to investigate motor adaptations in people with CNSLBP, specifically, by analysing kinematic variability differences, along with exploring their trunk muscle co-activation patterns and their clinical features in order to gain insights into potential associations that could be responsible for the differences in kinematic variability.

1.6.1 Specific objectives of this thesis:

1. To synthesise the evidence on whether the amount and structure of spinal kinematic variability is different in people with CNSLBP during various repetitive trunk movements when compared to asymptomatic individuals (i.e., including movements between thoraco-lumbar and/or lumbo-sacral segments) *(Chapter Two).*

2. To analyse kinematic variability of two spine segments (thoracic and lumbar) in people with CNSLBP compared to asymptomatic individuals while performing repetitive trunk flexion-extension movements at varying speeds during real-time tracking task using a novel approach, in addition to investigate trunk muscle co-activation patterns and observe temporal differences while tracking the feedback *(Chapter Three).*
3. To assess kinematic variability of two spine segments (thoracic and lumbar) in people with CNSLBP compared to asymptomatic individuals while performing a cyclic lifting task in a multi-planar pattern *(Chapter Four).*
4. To apply a novel method to assess kinematic variability in asymptomatic individuals without CNSLBP via parameters of the HA during repetitive trunk movements between three spinal segments (thoracic, lumbar, and sacral) with changing planes of motion and speed. Moreover, to examine trunk muscle co-activation patterns and its relationship with kinematic variability *(Chapter Five).*
5. To examine kinematic variability in people with CNSLBP using the novel parameters of the HA compared to asymptomatic individuals, as well as to measure trunk muscle co-activation during repetitive trunk movements and its relationship with kinematic variability *(Chapter Six).*
6. Finally, an additional objective to each experimental study in this thesis that recruited individuals with CNSLBP, was to explore the clinical characteristics of those individuals and if possible, assess the presence of any potential correlations between kinematic variability and the reported clinical features such as levels of pain intensity, disability and fear of movement *(Chapter Three, Four, and Six).*

1.7 Thesis chapters overview

The objectives of this thesis have been pursued through a series of studies, organised into separate chapters **(Figure 1.7)**. The presented results aim to aid researchers and healthcare practitioners to further understand movement adaptations in people with CNSLBP, particularly focusing on kinematic variability. These findings are intended to provide valuable insights that can enhance the examination and possibly intervention methods for individuals with CNSLBP.

Chapter One has set the scene for the following chapters by providing an overall summary in order to understand spinal movement and motor adaptations in response to pain, specifically differences in kinematic variability, in people with CNSLBP compared with asymptomatic individuals, and how the measures of variability are commonly quantified. *Chapter Two,* a systematic review, focuses on kinematic variability during repetitive trunk movements in people with CNSLBP compared to asymptomatic individuals, in order to answer objective one of the thesis. *Chapter Three,* reports the results of an observational study focused on kinematic variability in people with CNSLBP compared to asymptomatic individuals while performing a real-time tracking task in addition to investigating trunk muscle co-activation patterns and observing any temporal difference in tracking the feedback provided while repetitively flexing and extending the trunk. Moreover, the study aimed to assess any potential correlations between kinematic variability and reported clinical features. *Chapter Four,* reports results of an observational study, which focused on investigating kinematic variability differences in people with CNSLBP compared to asymptomatic individuals while performing a loaded cyclic lifting task in a multi-planar pattern. Moreover, to explore the clinical characteristics of those with CNSLBP compared to asymptomatic individuals. *Chapter Three and Four,* explored kinematic variability using linear measures during two different functional tasks that require different demands (*Chapter Three* while sitting, *Chapter*

Four while standing) in order to gain an understanding of how people with CNSLBP adapt to pain during repetitive trunk movements.

Chapter Five, is a methodological chapter, reporting the results of an observational study that introduces a novel method assessing kinematic variability of the thoracic and lumbar spine using parameters of the HA to test asymptomatic individuals during repetitive trunk movements while also analysing possible correlations with trunk muscle co-activation patterns. *Chapter Six,* is an observational study which uses the data of the asymptomatic individuals in *Chapter Five* as a control group to compare differences in kinematic variability with CNSLBP people via the novel parameters of the HA. Moreover, the study assesses correlations between kinematic variability and trunk muscle co-activation as well as clinical features in those with CNSLBP. The final chapter, *Chapter Seven*, summarises the main research outcomes of the thesis, including a general discussion of the collective research, strengths and limitations of the work, clinical implications, and suggestions for future research.

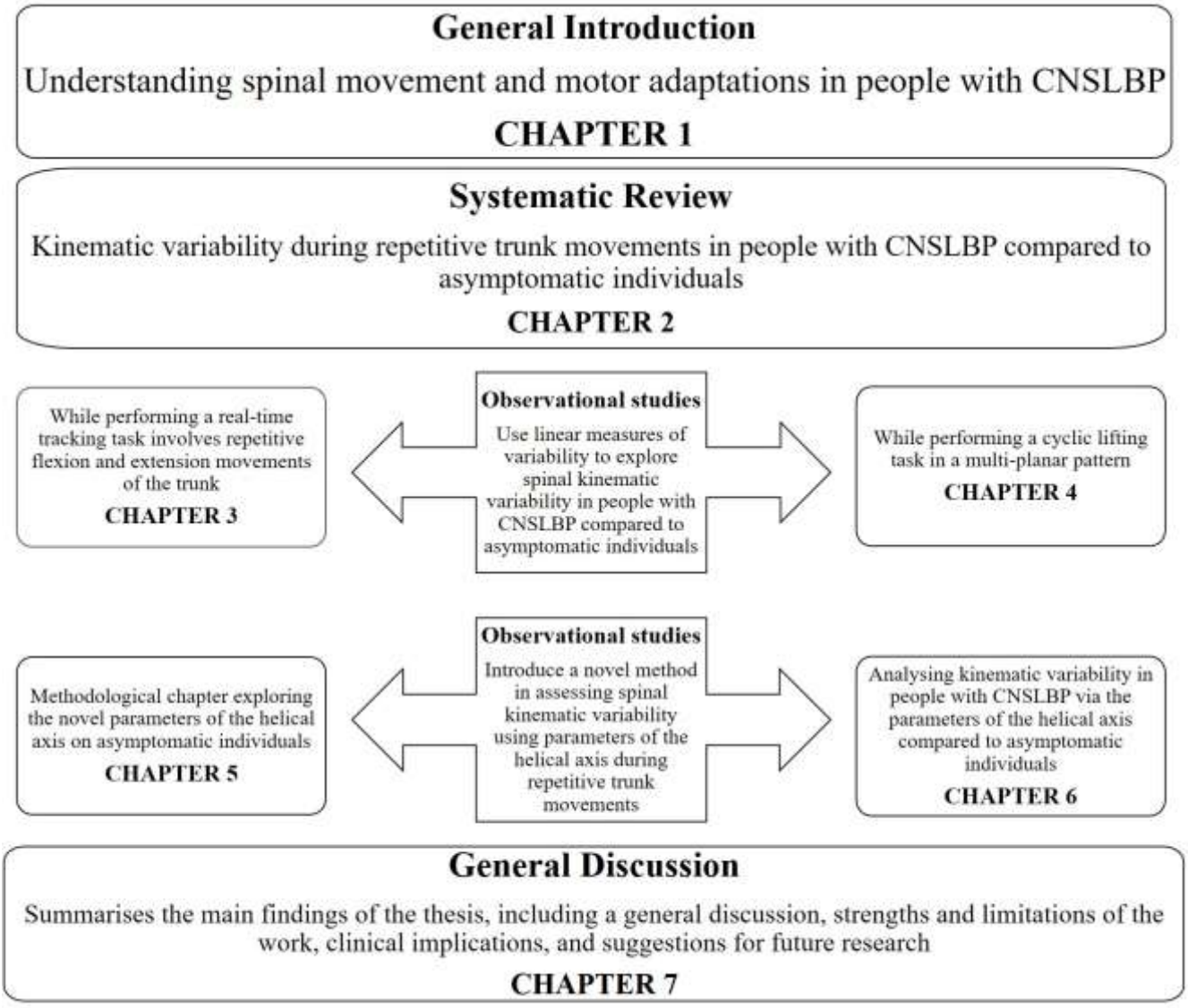


Figure 1.7: **Flow chart showing the thesis structure and the major research issues addressed in each chapter**

CHAPTER 2

IS MOVEMENT VARIABILITY ALTERED IN PEOPLE WITH CHRONIC NON-SPECIFIC LOW BACK PAIN? A SYSTEMATIC REVIEW

This chapter reports in full the contents of a published manuscript by the thesis author (Alsubaie et al., 2023a). It includes verbatim text from the published manuscript with some modifications to fit for the purpose of the thesis and to avoid repetition. Additionally, the methodology of this chapter has been previously published in a protocol paper before conducting the systematic review (Alsubaie et al., 2021b)

Publications and Presentations:

1. **Amal M. Alsubaie,** Masood Mazaheri, Eduardo Martinez-Valdes, and Deborah Falla. 2021a. Is movement variability altered in people with chronic non-specific low back pain: a protocol for a systematic review, *BMJ Open*, 11(5), p.e046064 **(Appendix 1)**
2. **Amal M. Alsubaie**, Masood Mazaheri, Eduardo Martinez-Valdes, and Deborah Falla. 2023a. Is movement variability altered in people with chronic non-specific low back pain? A systematic review, *PLOS ONE*, 18(6), p.e0287029 **(Appendix 2)**

2.1 Abstract

Variability in spine kinematics is a common motor adaptation to pain, which has been measured in various ways. However, it remains unclear whether LBP is typically characterised by increased, decreased or unchanged kinematic variability. Therefore, the aim of this review was to synthesise the evidence on whether the amount and structure of spine kinematic variability is different in people with CNSLBP. Electronic databases, grey literature, and key journals were searched from inception up to August 2022, following a published and registered protocol.

Eligible studies must investigated kinematic variability in CNSLBP people (adults ≥18 years) while performing repetitive functional tasks. Two reviewers conducted screening, data extraction, and quality assessment independently. Data synthesis was conducted per task type and individual results were presented quantitatively to provide a narrative synthesis. The overall strength of evidence was rated using the Grading of Recommendations, Assessment, Development and Evaluation guidelines. Fourteen observational studies were included in this review. To facilitate the interpretation of the results, the included studies were grouped into four categories according to the task performed (i.e., repeated flexion and extension, lifting, gait, and sit to stand to sit task).

The overall quality of evidence was rated as a very low, primarily due to the inclusion criteria that limited the review to observational studies. In addition, the use of heterogeneous metrics for analysis and varying effect sizes contributed to the downgrade of evidence to a very low level. Individuals with CNSLBP exhibited altered motor adaptability, as evidenced by differences in kinematic movement variability during the performance of various repetitive functional tasks. However, the direction of the differences in movement variability was not consistent across studies.

2.2 Introduction

As highlighted in *Chapter One*, people with LBP move differently than pain free individuals (Hodges and Tucker, 2011, Solomonow, 2011). However, the underlying mechanisms of motor adaptations to pain still require further clarification at both the micro (e.g., single motor neuron) and macro (e.g., whole muscle behaviour) levels (Hodges and Tucker, 2011). One common motor adaptation to pain is changes in spine kinematics, such as angular displacement, angular velocity, smoothness, and variability of movement (Hodges and Smeets, 2015, Hodges and Tucker, 2011, van Dieën et al., 2017). As an example, one study showed that people with LBP show more variability in coordination between the spine and pelvis during sit-to-stand, which is likely a strategy to find an optimal pain-free pattern (Jangjoo et al., 2022).

Several theories have been proposed previously as outlined in *Chapter One* to describe natural variability in motor performance (Kamm et al., 1990, Scholz and Schöner, 1999, Summers and Anson, 2009). Some theories propose that decreased variability generally indicates a highly stable and coordinated behaviour (Stergiou and Decker, 2011). Increased variability could also be considered a beneficial component for motor performance, as it may reduce the risk of injury by distributing joint loads (Nordin and Dufek, 2019). However, it is not well established how trunk movements should ideally be performed in terms of the adequate amount of motor variability, stability and complexity to achieve a coordinated movement that doesn't predispose an individual's spine to injury, specifically during dynamic and repetitive tasks (Cowin et al., 2022).

Differences in motor variability in people with LBP has been assessed in various ways, including assessing the variability of kinetic, kinematic measures, coordinative aspects of a movement pattern, as well as muscle activity patterns (Srinivasan and Mathiassen, 2012). However, it remains unclear whether movement in people with LBP is typically characterised by increased, decreased, or unchanged variability (Asgari et al., 2015, Dideriksen et al., 2014, Dijk et al., 2021, Saito et al., 2021).

One possible reason for this is the large variation seen across individuals with LBP (Fourney et al., 2011). Another possible reason is the use of various linear and non-linear measurement tools to quantify the amount and structure of motor variability, respectively (Harbourne and Stergiou, 2009, Komar et al., 2015, Krüger et al., 2017). Both the amount and structure of variability functionally represent different aspects of motor performance and can vary independently from one another (Harbourne and Stergiou, 2009).

Systematic reviews have examined biomechanical and neuromuscular changes in people with LBP, and to a lesser extent, the motor variability during specific functional tasks, such as gait and quiet standing (Koch and Hänsel, 2018, Koch and Hänsel, 2019), or balance performance for a specific age category, i.e., elderly (Ge et al., 2021). However, only scoping reviews have examined motor variability in the presence of spinal pain (Dijk et al., 2021, Saito et al., 2021). Both reviews revealed large heterogeneity between study designs and results. Dijk et al. (2021), attributed the inconsistent findings between studies to differences in normalisation methods, changes in functional tasks, and differences in pain intensity or fear-avoidance behaviours of those with LBP. Although Dijk et al. (2021) included participants with chronic LBP, motor variability was assessed based on EMG recorded from the thoracolumbar region and kinematic movement patterns in all body regions (e.g., including the knee joint) during functional tasks.

To date, no systematic review has synthesised findings on kinematic variability of the spine in people with CNSLBP during the performance of repetitive functional tasks. Therefore, the systematic review in this chapter addresses objective one of the thesis and aims to synthesise the evidence on whether the amount and structure of motor variability in kinematics (such as joints displacement, acceleration, and velocity) are different in people with CNSLBP at the thoraco-lumbar and/or lumbo-pelvic levels.

2.3 Methods

This systematic review was planned according to the updated guidelines of the Cochrane Back and Neck Group (Furlan et al., 2015), Cochrane Handbook for Systematic Reviews of Interventions (Higgins JPT, 2022), and the review is reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement **(Appendix 3)** (Moher et al., 2009). The protocol was registered a priori with PROSPERO, Centre for Reviews and Dissemination, University of York, (CRD42020211580) on 10/12/2020, and the protocol was published in advance (Alsubaie et al., 2021b) **(Appendix 1)**.

2.3.1 Eligibility criteria

Eligibility criteria were defined with the PICOS framework (P: Population; I: Indicator/ Exposure; C: Comparator; O: Outcome(s); S: Study design) (Higgins JPT, 2022, Smith et al., 2011). Eligibility criteria are summarised in **Table 2.1**.

Table 2.1: **Summary of inclusion and exclusion criteria**

Inclusion criteria	
Population	Adults (≥18 years old), men and women with chronic non-specific LBP
Indicator/Exposure	Motion analysis systems (e.g., optoelectronic systems, inertial measurement unit sensors, etc.)
Comparison	Healthy controls
Outcomes	Amount or structure of kinematic variability based on linear or non-linear measures
Study Type	Quantitative cross-sectional observational studies
Exclusion criteria	

Population	Individuals under the age of 18, people with LBP attributable to a specific pathology, concurrent systemic disorders, surgery, cardiovascular conditions or pregnancy
Indicator/Exposure	None
Comparison	Individuals under the age of 18, concurrent systemic disorders, surgery, cardiovascular conditions or pregnancy
Outcomes	Studies using spatio-temporal parameters based on neuromuscular variables (i.e., EMG signals) only
Study Type	Cadaveric or animal studies, single-subject case reports, longitudinal cohort studies, interventional studies including both randomised and non-randomised clinical trials, reviews, meta-analysis and study protocols as well as studies not written in English.

Population

The population of interest were men and women with an age of 18 years and above with CNSLBP that persisted for at least 3 months with no diagnosable underlying pathology (Dionne et al., 2008). They did not present with concurrent systemic disorders including rheumatic and neuromuscular disorders, spinal deformity or surgery, cardiovascular conditions and pregnancy. Studies that recruited people with LBP due to trauma, fractures, spinal stenosis, or radicular pain were excluded from this review.

Indicator

Studies were considered eligible if they used motion capture systems (e.g. optoelectronic systems, inertial measurement unit sensors, etc.) to quantify variability of spinal movement at the level of thoraco-lumbar and/or lumbo-pelvic regions (Harbourne and Stergiou, 2009, Stergiou et al., 2006).

Comparison

For the purpose of this review, adults without a history of LBP represented the control group. No concurrent systemic disorders including rheumatic and neuromuscular disorders, spinal deformity or surgery, cardiovascular conditions and pregnancy were present in the participants.

Outcomes

The main outcome of interest was kinematic motor variability, either the amount or structure, measured based on a wide range of movement variables during repetitive functional tasks. Multiple kinematic outcome measures that quantified the spinal movement at the level of thoraco-lumbar and/or lumbo-pelvic regions were considered for the variability measures (i.e., amount or structure) including joints displacement (or ROM), acceleration, velocity, or coordination (a measure between two kinematic variables). The decision to limit studies to thoraco-lumbar and/or lumbo-pelvic kinematics was made to maintain a specific focus within the research scope. This was driven based on the heterogeneous findings identified in previous reviews, leading to the decision to pursue a precise protocol to ensure more homogeneous findings. While this choice may exclude some studies, it is intended to ensure a more targeted investigation.

Study design

Observational cross-sectional studies were included. The following study types were excluded: cadaveric or animal studies, single-case studies, longitudinal cohort studies, and interventional studies including both randomised and non- randomised clinical trials, reviews, meta-analysis, study protocols as well as studies not written in English.

2.3.2 Information sources and search strategy

The following databases were searched initially from inception to 14th December 2020 by one reviewer (AMA); updated up to 23rd August 2022 by the same reviewer (AMA): MEDLINE (OVID Interface), EMBASE (OVID Interface), CINAHL (EBSCO Interface), ZETOC (EBSCO Interface), Web of Science, PubMed and Scopus. Reference lists of included studies and relevant reviews were checked. Moreover, hand searching was conducted of relevant key journals including: Journal of Electromyography and Kinesiology, Clinical Biomechanics, Journal of Biomechanics, Human Movement Science, The Clinical Journal of Pain, Spine, Journal of Orthopaedic & Sports Physical Therapy, Musculoskeletal Science and Practice, and Journal of Back & Musculoskeletal Rehabilitation.

The search strategy was developed based on the PICOS framework using medical subject headings (MESH) identified during the scoping search (**Table 2.1)**. A complete search strategy example used in MEDLINE (OVID interface) was provided in the published protocol (Alsubaie et al., 2021b) **(Appendix 1)**. Appropriate modifications with relevant syntax and MESH terms was performed to the main search strategy to adapt for other databases and ensure consistency. Grey literature was included in the search using the British National Bibliography for Report Literature (BNBRL), OpenGrey database, ProQuest Dissertations & Theses Global and EThOs to reduce the risk of publication bias. Key congresses and meetings in the field were searched from 2017 to 2022, including the World Congress of Biomechanics (WCB) and the International Society of Electrophysiology and Kinesiology (ISEK) congresses.

2.3.3 Study selection

Records were retrieved from databases and imported into EndNote V.X9 (Clarivate Analytics). After the removal of duplicates, eligible studies were selected by two reviewers (AMA, MM) who

independently conducted title and abstract screening of all retrieved studies against the predetermined eligibility criteria and categorised articles into ‘include’, ‘unsure’ (e.g., needs full text review) and ‘exclude’. Eligible full-text studies were screened by one reviewer (AMA) and the selection decision was confirmed by the second reviewer (MM). Any disagreement between the reviewers in the study selection process was resolved by discussion.

2.3.4 Data extraction and data items

One reviewer (AMA) extracted the data from the eligible studies using a customised data extraction form and then the accuracy was confirmed by a second reviewer (MM). A third reviewer (DF) was available to mediate any disagreements. WebPlotDigitizer software was used to extract data from figures when text and tables were not sufficient to obtain the main outcome results. The following components were extracted: Population ((inclusion/exclusion criteria, sample size and demographic (i.e., sex, age, height, weight, body mass index) and clinical characteristics (such as pain intensity and duration, disability level, fear of movement, and other psychological factors)); Indicator (type of task performed, measurement instrument, and spine region assessed); Outcome (variability measure/metrics); and Results (mean and SD of outcome measures and their statistical significance).

2.3.5 Risk of bias assessment

Due to the lack of a gold-standard instrument designed to quantify the quality of observational cross-sectional studies, the methodological quality of the included studies was assessed using a modified version of Downs and Black Scale (D&B), designed for assessing the quality of both randomised and non-randomised studies (Downs and Black, 1998). Among various tools available, D&B is the most used tool in literature to assess methodological quality for observational studies (Hootman et al., 2011). This was done independently by two reviewers (AMA, MM). The modified

version consists of 4 domains (12 items) including quality of reporting (7 items), the generalisability of results or external validity (1 item), the relationship between LBP and outcomes, known as internal validity (3 items) and the adequacy of sample size or study power (1 item). Items 4, 5, 6 and 11 were specifically implemented from a previous review to fit the study design of the current review (Mazaheri et al., 2021). The scoring was simplified to a choice of 0 ("no"/"unable to determine") or 1 point ("yes"). Therefore, the total scores range from 0 to 12 and higher scores indicate a better methodological quality of the study (Silverman et al., 2012, Torres Sanchez et al., 2019). However, for the purpose of this review, the total score was presented with a percentage score; moderate quality when 60–74% of the applicable criteria was met; >75% as high and <60% as low quality (Irving et al., 2006, Munn et al., 2010).

2.3.6 Summary measures and data synthesis

Due to the heterogeneity of the studies (i.e., nature of the task, spine region, the used variability measure), meta-analysis was not possible and therefore a narrative synthesis was conducted. The studies were sub-grouped according to the nature of the task performed during the assessment. In contrast to previous reviews (Dijk et al., 2021, Saito et al., 2021), visualisation of quantitative data was considered important in this study and hence effect estimates and their confidence interval for each study was presented in a forest plot without producing the overall estimate of effect. Results were reported using mean and standard deviation (SD). When standard error (SE) was reported, SD was calculated using the formula (Cumpston et al., 2019):

$$SD = SE * \sqrt{N}; \text{ N: sample size}$$

When the LBP population was presented as subgroups (i.e., male/female, low disability/high disability, athletes/non-athletes, or different pain intensity levels (1-10)), we followed the Cochrane guidelines handbook and used appropriate formulae for combining groups (Cumpston et al., 2019).

Differences between the LBP and control groups were summarised using the standardised mean difference (SMD) and 95% confidence intervals (95% CI). Forest plots were produced in RevMan software (v.5.4 Cochrane Collaboration) (Prictor and Hill, 2013).

2.3.7 Quality of evidence

The quality of evidence was assessed for the main outcome domain per task type using the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) approach (Atkins et al., 2004). The level of evidence was then graded by each reviewer independently where ratings were made as per `high', `moderate', `low' or `very low' (Montgomery et al., 2019). Initially, since only observational studies were included, low quality of evidence was assigned to the primary outcome domain per task type performed (Balshem et al., 2011). Then, the quality of evidence was rated considering five factors (limitations, inconsistency, indirectness, imprecision, and publication bias) (Balshem et al., 2011). The D&B individual score for each study was integrated into the GRADE approach to define the study limitations of evidence (for each outcome domain) (Guyatt et al., 2011). Therefore, if the evidence was mainly obtained from studies with low methodological quality (D&B score <60%), limitations were described as serious. No limitation was reported with moderate methodological quality studies (D&B range from 60 to 74%). Finally, the level of quality of evidence was upgraded when most of the findings came from studies with high methodological quality (Guyatt et al., 2011). Overall, the level of evidence was identified as ‘High’, ‘Moderate’, ‘Low’, or ‘Very Low’ (Balshem et al., 2011).

2.4 Results

2.4.1 Study selection

The database search retrieved a total of 6949 records that were identified through both database and hand searching. After the removal of duplicates, 4775 records were title and abstract screened by the two reviewers. A total of 59 studies were retained for full text screening. Finally, 14 studies were obtained for quantitative narrative synthesis. The search strategy and reasons for exclusion are provided in the PRISMA flow chart in **Figure 2.1**. The specific reasons for exclusion for each study can be found in the supporting documents in the published systematic review **(Appendix 2).**

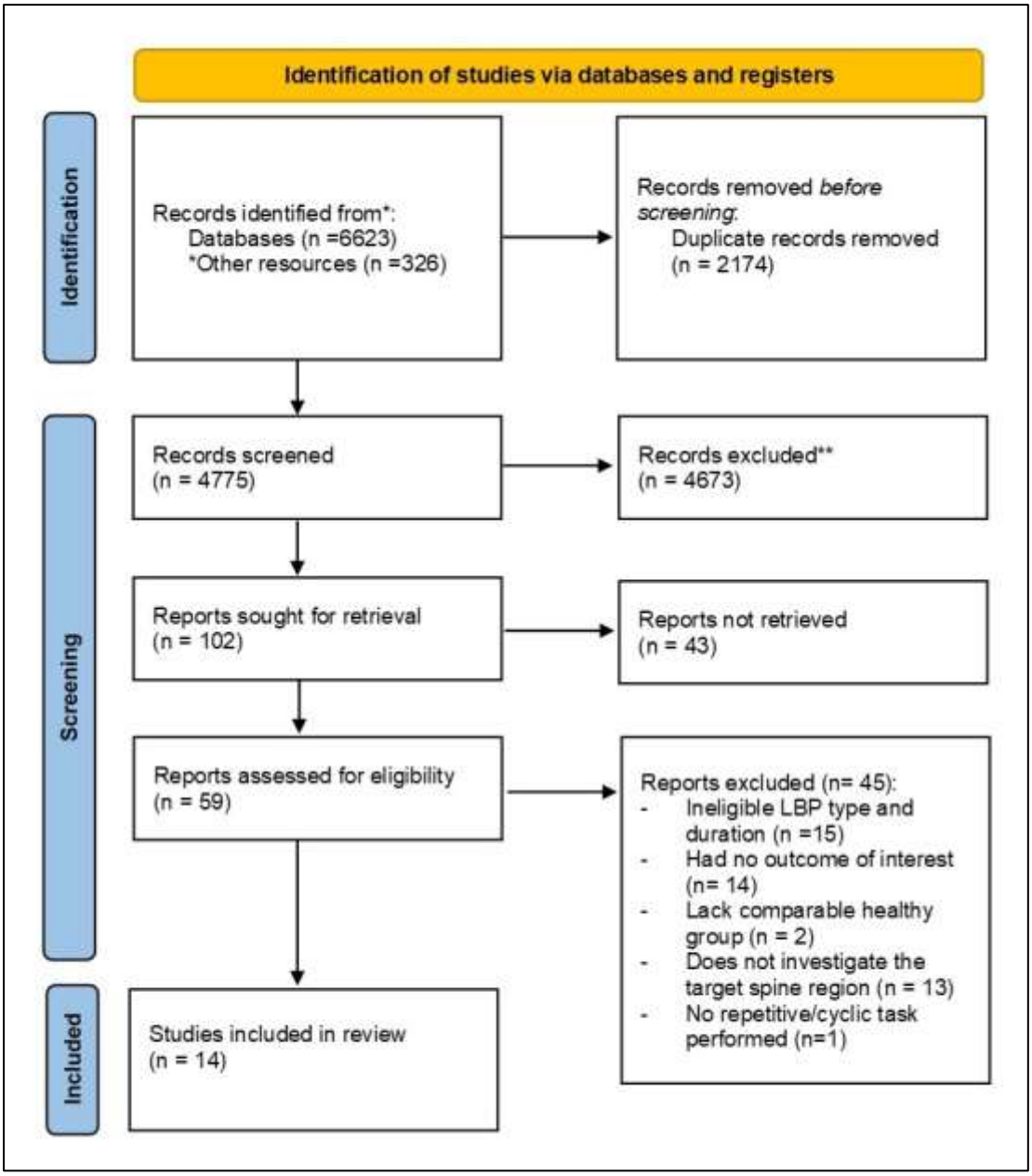


Figure 2.1: **Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 flow diagram. *Other resources that were identified through searching the gray literature and hand search.**

2.4.2 Characteristics of included studies

All of the 14 included studies were observational studies published between 2001 and 2022 (Bauer et al., 2017, Bauer et al., 2015, Dideriksen et al., 2014, Ebrahimi et al., 2017, Fujii et al., 2022, Graham et al., 2014, Ippersiel et al., 2018, Lamoth et al., 2006a, Lamoth et al., 2006b, Mokhtarinia et al., 2016, Moreno Catalá et al., 2018, Pranata et al., 2018, Seay et al., 2011, Vogt et al., 2001). In total, 380 people with CNSLBP were included (women: 41%; men: 55% except one study that did not mention the women/men ratio (Seay et al., 2011)) and 276 healthy people. The mean age of LBP participants ranged from 20.8 to 44.1 years with average pain intensity of 3.1 out of 10 on a numerical pain scale and an average pain duration of 34.7 months. The average disability level was 17.5% in studies that used Oswestry-disability-index (ODI) and 5.3 in studies that used Roland–Morris Disability Questionnaire (RMDQ), indicating a minimal level of disability. Only three studies (Dideriksen et al., 2014, Fujii et al., 2022, Lamoth et al., 2006a) assessed the fear-avoidance behaviour and beliefs using Tampa Scale for Kinesiophobia (TSK), with an average score of 30.9 indicating moderate levels of fear and avoidance (Chimenti et al., 2021), and only two (Dideriksen et al., 2014, Fujii et al., 2022) measured catastrophic thinking related to pain using the Pain Catastrophizing Scale (PCS), with an average score of 11.25.

To facilitate the interpretation of the results, the included studies were grouped into four categories based on the task performed. Detailed descriptions of the inclusion/exclusion criteria can be found in the supporting documents in the published systematic review **(Appendix 2),** and demographic and clinical characteristics of the included studies are presented in **Table 2.2**.

Table 1.2: **Demographic and clinical characteristics of included studies;**

PCS: Pain Catastrophizing Scale, **NR**: Not Reported, **VAS:** Visual Analog Scale, **NRS**: Numerical Rating Scale, **NPRS:** Numeric Pain Rating Scale, **SF-36:** 36-Item Short Form Survey, **STAI**: State-Trait Anxiety Inventory, **BMI:** Body Mass Index, **FreBAQ**: Fremantle Back Awareness Questionnaire, **λmax:** Maximum Lyapunov exponent: **PSIS**: posterior superior iliac spine

First Author	**Sample size; sex (f/m); age (yrs); height (cm); weight (kg); BMI (kg/m²)**			**LBP characteristics**		
	LBP	**Healthy control**	**Matching criteria for two groups**	**Intensity; duration**	**Disability level**	**Psychological status**
1. Repeated Flexion and Extension task						
Graham et al. 2014 (Graham et al., 2014)	10; 6/4; 20.8 (1.4); 175.9 (14.0); 71.8 (14.1); NR	10; 6/4; 20.6 (1.0); 173.7 (11.1); 72.5 (12.0); NR	Sex; age; height; weight	NR; 24.4±23 months	ODI (0-50): 7.8 (3.5); RMDQ (0-24): 4.0 (2.1)	NR
Mokhtarinia et al. 2016 (Mokhtarinia et al., 2016)	22; 0/22; 30.2 (6.1); 177 (7.7); 74.5 (7.7); 23.9 (3.3)	22; 0/22; 27.4 (5.1); 174 (8.2); 71.4 (10); 23.5 (3.5)	Age; height; weight	VAS (0-10) < 2; NR	NR	NR
Bauer et al. 2017 (Bauer et al., 2017)	59; 29/30; 39.1 (12.8); NR; NR; 24.0 (3.6)	27; 15/12; 39.6 (11.6); NR; NR; 22.7 (2.8)	NR	NRS ≥ 1; NR	ODI > 8% moderate disability	STarT Back Screening Tool-psychological subscale: < 4

2. Lifting task						
Dideriksen et al. 2014 (Dideriksen et al., 2014)	17; 10/7; 32.5 (9.6); 177. 4 (9.6); 74.3 (12.8); NR	17; 9/8; 29.7 (7.3); 174.8 (10.3); 69.2 (14.0); NR	Sex; age	NRS: 3.1 (2.2); 34.2 (29.3) months	ODI: 14.2 % (7.2)	SF-36 (total) (0–100): 66.9 ± 12.2 Physical (0–100): 60.9 ± 14.2 Mental (0–100): 67.6 ± 14.1 TSK (17–68): 31.8 ± 5.9 PCS (0–52): 16.1 ± 8.5 STAI (20–80): 40.2 ± 7.1
Bauer et al. 2015 (Bauer et al., 2015)	63; 31/32; 39.2 (12.5); NR; NR; 24.2 (3.9)	31; 17/14; 40.1(12.1); NR; NR; 22.7(2.9)	NR	NRS: 3.3 (1.5) ;NR	ODI > 8%, moderate disability	SBT psychosocial subscale (≥4 high risk): < 4
Moreno Catalá et al. 2018 (Moreno Catalá et al., 2018)	*Non-athletes:* 15; 5/10; 27 (1); 178 (7); 78 (17.7); 24.3 (4.3) *Athletes:* 15; 5/10; 23 (2); 175 (10);72.9 (10.7); 23.6 (1.6) *Combined:* 30; 10/20; 25 (2.6); 176.5 (8.6); 75.5	*Non-athletes:* 14; 5/9; 24 (3); 175 (11); 70.3 (11.2); 22.7 (2.5) *Athletes:* 15; 5/10; 23 (3); 178 (9); 73.4 (13.4); 22.8 (2.4) *Combined:* 29: 10/19; 23.5 (2.9); 176.5 (9.9); 71.9	Age; height; weight	VAS: 3.92±1.70 (Non-athletes) **,** 4.54±1.82 (athletes)**,** 4.2 ±1.8 (combined); ≥ 12 months	NR	NR

	(14.6); 23.9 (3.2)	(12.2); 22.8 (2.4)				
Pranata et al., 2018 (Pranata et al., 2018)	*High disability (ODI > 20%):*18; 12/6; 46.7 (11.8); 170 (10); 71.5 (14.0); 24.8 (3.8) *Low disability (ODI < 20%):* 25; 11/14; 42.3 (11.1); 174 (10); 81.6 (19.0); 26.0 (5.0) *Combined:* 43; 23/20; 44.1 (11.5); 172.3 (10); 77.3 (17.6); 25.5 (4.5)	29; 17/12; 37.8 (11.5); 167 (10); 73.4 (17.6); 25.9 (5.6)	Sex; age; BMI	NRS (0-10): 4.5 ± 1.9 (high disability, 3.0 ± 1.6 (low disability)**,** 3.6 ± 1.9 (combined) ; 155.2 ± 173.2 months (high disability), 110.2 ± 107.8 months (low disability), 129 ± 138.8 (combined)	ODI (0-100%): 34.4 ± 10.9 (high disability)13.2 ± 4.9 (low disability); 22 ±13.2 (combined)	NR
Fujii et al., 2022 (Fujii et al., 2022)	31; 0/31; 30.5 (6.0); 172.7 (3.6); 65.5 (4.2); NR	20; 0/20; 28.1 (5.2); 172.0 (4.8); 66.7 (9.0); NR	NR	NRS in the past 4 wks (0-100): 3.6 (1.7); 14.7 (14.9) months	RMDQ (0-24): 2.1 (1.4)	TSK-11 (11–44): 21.9 (5.0). PCS-4 (0–16): 6.4 (3.9). Fre-BAQ (0–36): 7.5 (6.5)
3. Gait						
Vogt et al. 2001 (Vogt et al., 2001)	*Male:* 21; NA; 36.3 (1.7);	*Male:* 16; NA; 34.8 (5.2);	NR	VAS (0-10): 3.7	ODI: 27.67%;	NR

	173.3 (9.1); 77.8 (16.3); 25.8 (4.1) *Female:* 13; NA; 32.1 (3.4); 175.9 (5.6); 76.9 (12.5); 24.8 (3.3) *Combined:* 34; NA; 34.7 (3.2); 174.2 (7.9); 77.5 (13.1); 25.4 (3.7)	178.6 (4.7); 77.6 (6.5); 25.5 (2.4) *Female:* 6; NA; 29.4 (1.3); 170.3 (9.9); 71.5 (4.9); 23.7 (2.6) *Combined:* 22; NA; 33.3 (5.0); 176.3 (7.3); 75.9 (6.6); 25.0 (2.5)		(range, 3-5.3); NR	(range, 24–48%)	
Lamoth et al. 2006a (Lamoth et al., 2006a)	19;11/8; 38 (21–52); 173 (154–188); 74.4 (49–97); NR	14; 5/9; 31 (20–46); 180 (158–198); 72.5 (52-105); NR	Sex; age; height; weight	VAS: 5.6 (3); 14.4 (3.5-36) months	RMDQ: 10 (6)	TSK: 39 (6.8)
Lamoth et al. 2006b (Lamoth et al., 2006b)	12; 7/5; 36.8 (10.9); 174 (11); 72.4 (14.5); NR	12; 5/7; 30±8.1; 180 (12); 73.3 (16.6); NR	Age; height; weight	NR; NR	NR	NR
Seay JF et al. 2011 (Seay et al., 2011)	14; NR; 35.71 (10.90); 171 (12); 73.94 (13.42); NR	14; NR; 29.90 (8.45); 169 (10); 63.94 (10.06); NR	Age; height; weight	VAS (1-10): 0.8 (1.4); NR	ODI (0-100%) : 7.9% (6.3)	NR

Ebrahimi et al. 2017 (Ebrahimi et al., 2017)	10; 5/5; 29.4 (6.38); 68.07 (12.92); 164.4 (8.19); NR	10; 5/5; 29.6 (5.64); 62.38 (13.12); 167.40 (7.36); NR	Sex, age, height, and weight	NRS: 5.1 (0.88); NR	ODI: 37.30% (12.66)	NR
4. Sit to stand to sit (STS) task						
Ippersiel et al. 2018 (Ippersiel et al., 2018)	16; 11/5; 30 (9); NR; 78.6 (18.5); NR	21; 10/11; 27 (10); NR; 67.4 (10.0); NR	NR	NPRS (0-10): 3.4 (1.1); 109.9 (113.5) months	ODI: 25.3%(7.4)	NR

2.4.3 Narrative synthesis of results

The main findings of each study are summarised in **Table 2.3** with more detailed description of the task performed **(supporting documents of Appendix 2).** The outcome measures of interest used in the eligible studies were drawn from either linear or non-linear metrics or both. The studies exhibited a significant degree of heterogeneity with respect to the spinal regions examined, the type of the tasks performed, and the metrics used to analyse data. Therefore, meta-analysis was inappropriate and individual results are presented quantitatively using RevMan. The interpretation of the reported effect sizes were based on the mean difference where (0.0-0.2) considered small effect, (0.4-0.5) medium, and (0.8-3.0) large effect (Lee, 2016).

Table 2.3: **Measurement protocol of included studies**

First Author	Task performed	Instrument used	Spine region assessed	Outcome measures	*p* value
1. Repeated Flexion and Extension task					
Graham et al. 2014 (Graham et al., 2014)	Two randomised trials, symmetric and asymmetric, of 30 repetitive and continuous trunk flexion and extension movements from standing position, with a constrained pelvis and their hands held together	Electromagnetic motion sensors (Liberty, Polhemus, Colchester, VT, USA)	Lumbar spine (over T12 and S1)	Maximum Lyapunov exponent, λmax **(**Local dynamic spine stability)	**Dynamic stability: Group:** *p*=0.440
Mokhtarinia et al. 2016 (Mokhtarinia et al., 2016)	30 cycles of repeated trunk flexion–extension (touching target placed at knee level followed by returning to upright position)	3D video-motion analysis system (VICON, Oxford, UK)	Lumbar–pelvis (T10-PSIS-ASIS)	Deviation phased DP (sagittal plane)	**DP (Degree): Group:** *p*=0.75
Bauer et al. 2017	Repeated trunk flexion and	Inertial measurement	Lumbar between 1st lumbar and	Determinism % and	**Pre-Fatigue condition:**

(Bauer et al., 2017)	extension test in sitting position	unit (IMU) system (Valedo ®Motion, Hocoma AG, Volketswil, Switzerland)	2st sacral vertebra	Sample entropy of angular displacement and velocity	**Angular Displacement Group: %DET:** *p*=0.138 **SaEn**: *p*=1.0 **Angular velocity Group: %DET:** *p*=0.57 **SaEn**: *p*=<0.001*
Dideriksen et al. 2014 (Dideriksen et al., 2014)	Repetitively move a box (5 kg) between two shelves, located at knee and shoulder height	Epionics SPINE (Epionics Medical GmbH, Potsdam, Germany) with two sensor strips, each with 12 evenly spaced angle sensors (25 mm apart from one another); The bottom of the strip located at the posterior superior iliac spine (PSIS)	From PSIS 30 cm upward covering the whole spine	Determinism %	**%DET Group:** Average *p*= 0.54
2. Lifting task					
Bauer et al. 2015 (Bauer et al., 2015)	Pick up a box from standing position, 10 cycles	Inertial measurement unit IMU system (ValedoMotion, Hocoma AG, Volketswil, Switzerland)	Lumbar between 1st lumbar and 2st sacral vertebra	Recurrence (REC) and Determinism (DET) of angular displacement, velocity, and acceleration	**Angular displacement (AD) Group:** REC AD: *p*=0.018 DET AD: p=0.01*

					Angular velocity (AV) REC AV: p=0.03* DET AV: p=0.05* **Angular acceleration (AA)** REC AA: p=0.03* DET AA: P=0.05*
Moreno Catalá et al. 2018 (Moreno Catalá et al., 2018)	Lifting task, in which a pot (1.5 kg) was cyclically moved back and forth between two tables of different heights (40 cycles); participant standing in the middle of two tables	Vicon 624 system (Vicon Motion Systems, United Kingdom)	Lumbar-pelvis: Region between L4/L5 disk space and ninth thoracic vertebrae.	Maximum Lyapunov exponent (λmax)	**Dynamic stability (λmax):** **Group:** p=0.136
Pranata et al., 2018 (Pranata et al., 2018)	Lifting an 8-kg kettlebell up to the level of their abdomen using a self-selected pace and technique; repeated twice	12-camera Optitrack Flex 13 motion analysis system (NaturalPoint, Corvallis, OR)	Lumbar-pelvis in the sagittal plane	Deviation phase (DP)	**DP lumbar-hip (Degree):** **Group:** p=0.13

Fujii et al., 2022 (Fujii et al., 2022)	Lifting a box (520 × 365 × 305 mm) placed on the ground as quickly as possible to waist-height. In three different conditions	A 3D motion capture system with a four-charge-coupled device (CCD) camera (KinemaTracer, KisseiComtec, Matsumoto, Japan).	Upper and lower lumbar regions. (L3 spinous process and S1 spinous process)	Deviation phase (DP)	**DP (Degree):** **Flexion phase:** **Group:** p=0.10 **Extension phase:** **Group:** p=0.57
3. Gait					
Vogt et al. 2001 (Vogt et al., 2001)	Walking on a motorized treadmill at 4.5 km/h; data from a 30-second interval recorded while walking for approximately 3 minutes	Treadmill: a motorized treadmill (HPCosmos, Germany); Motion: 3D ultrasonic movement analysis system (Zebris CMS 70, Germany)	Thoracolumbar (markers placed on T12 and S1)	Coefficient of variation (CV)	**Stride-to-Stride CV:** **Group*:*** p< 0.001*
Lamoth et al. 2006a (Lamoth et al., 2006a)	Walking on a treadmill at a self-selected walking velocity succeeded by increasing velocity from 1.4 km/h to a maximally attainable walking velocity of up to	3D active marker movement registration system (Optotrak 3020, Northern Digital, Ontario, Canada)	T3, L2 spinous processes, and the sacrum (between posterior superior iliac spine PSIS)	SD relative phase between lumbar and pelvis rotations (transverse and frontal plane)	**Relative phase variability (Degree):** **Group:** Transverse plane: p=0.04* Frontal plane: p<0.01*

	7.0 km/h				
Lamoth et al. 2006b (Lamoth et al., 2006b)	Walking on a treadmill at six velocities in a fixed order: 6.2, 1.4, 3.8, 5.4, 2.2, and 4.6 km/h	3D active marker movement registration system (Optotrak 3020, Northern DigitalTM, Ontario, Canada)	Third thoracic vertebra (T3), second lumbar vertebra (L2), and the sacrum	SD relative phase between lumbar and– pelvis rotations (transverse and frontal plane)	**Relative phase variability (Degree):** **Group:** Transverse plane: p=0.03* Frontal plane: p<0.01*
Seay JF et al. 2011 (Seay et al., 2011)	Walking (at various speeds systematically increased from 2.88km/h in increments of 1.8km/h to 13.68 km/h	Treadmill: (Frappier Acceleration, Fargo, ND, USA and Advanced Mechanical Technologies, Incorporated, Waltham, MA, USA); Motion: 3D kinematic data were collected using eight high-speed cameras (Motion Analysis Corp., Santa Rosa, CA)	Pelvis–trunk (T12 L1 -L5 S1 inter-vertebral joint space) in sagittal, frontal and transverse plane	SD relative phase	**Relative phase variability (Degree):** **Group:** **Sagittal**: Walking: p=0.662 Running:p=0.122 **Frontal:** Walking:p=0.402 Running:p=0.985 **Transverse:** Walking:p=0.203 Running:p=0.022*
Ebrahimi et al. 2017 (Ebrahimi et al., 2017)	Walking barefoot along an 8-m walkway at a comfortable self-selected	An eight-camera motion analysis system (Proreflex, Qualisys	Upper and lower back – pelvis.	Deviation phase over stance and swing (sagittal plane)	**DP (degree):** **Group:** Stance*:* p=0.049* Swing: p=0.008*

	speed; at least 20 complete gait cycles for each limb captured	Track Manager® Ltd., Gothenburg, Sweden)			
4. Sit to stand to sit (STS) task					
Ippersiel et al. 2018 (Ippersiel et al., 2018)	Sit to stand to sit (STS) task with arms crossed over chest, including standing upright from sitting and return to sitting as quickly as possible, 10 trials	An electromagnetic TrakSTAR motion capture system with model 800 sensors (Ascension Technology, Milton, VT, USA)	The lower lumbar spine (L3-S1) and upper lumbar spine (T12-L3)	Deviation phase DP (sagittal plane)	**DP (degree): L3S1-T12L3:** **Group:** *p*=0.147

2.4.4 Type of task

Repeated flexion and extension

Three studies investigated movement variability during repeated flexion-extension task performed under symmetrical (n=3) (Bauer et al., 2017, Graham et al., 2014, Mokhtarinia et al., 2016) or asymmetrical (n=2) conditions (Graham et al., 2014, Mokhtarinia et al., 2016) (**Figure 2.2)**. One study used a linear measure known as deviation phase (DP) to quantify the amount of intersegmental coordination variability (Mokhtarinia et al., 2016). The other two studies employed non-linear measures, with one study characterising the structure of variability in angular displacement using maximum Lyapunov exponent (λmax) (Graham et al., 2014), and the other study assessing the

structure of variability in both angular displacement and velocity using percentage determinism (DET%), and sample entropy (SaEn) (Bauer et al., 2017). It is worth noting that λmax was defined as a measure of local stability, where lower λmax values is associated with higher stability (Graham et al., 2014), while DET% was described as a measure of predictability and SaEn as a measure of complexity (Bauer et al., 2017).

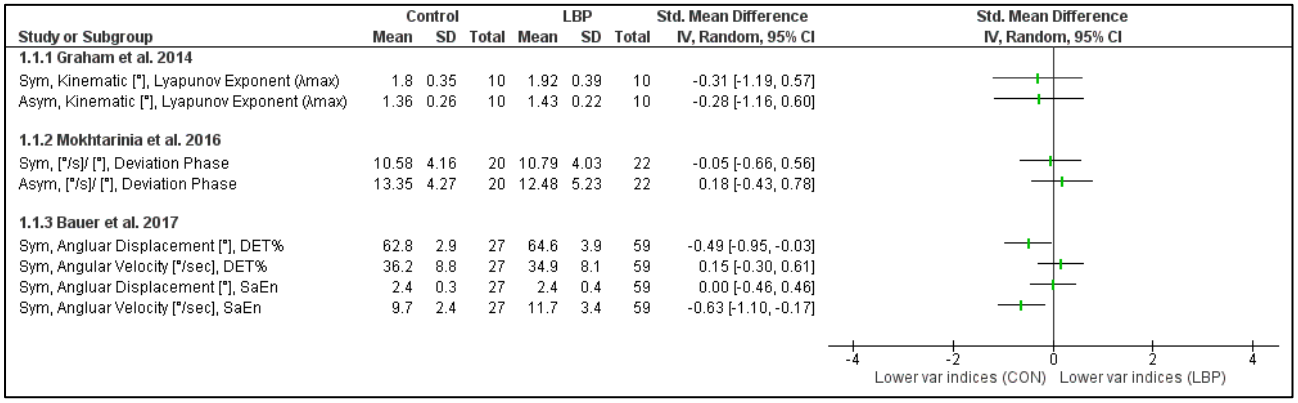


Figure 2.2: **Differences in movement variability between people with LBP and healthy controls (CON) while performing repeated flexion and extension tasks.**

Sym: symmetric; Asym: Asymmetric; %DET: Percentage determinism; SaEn: Sample entropy; Var: Variability.

Out of a total of eight measurements, only two measures from one study showed a significant difference in variability indices between people with and without LBP (Bauer et al., 2017). Those with LBP showed a higher level of complexity and less predictability in angular velocity (as indicated by high SaEn), but greater predictability in angular displacement (as indicated by high DET%). A more pronounced effect was observed for angular velocity (with a medium effect size) compared to angular displacement (with a small effect size). However, this effect was not reported in the study, as the main comparison focused on detecting the effect of fatigue using a linear mixed model. Therefore, the effect of pain was only measured based on the pre-fatiguing condition using the reported means, SDs, and sample sizes, which was significant only for SaEn on angular velocity (p <0.001). Overall,

only one of the three studies reported a small to medium effect of LBP status on variability measures during the repetitive trunk flexion and extension task, indicating a reduction in predictability and an increase in complexity.

Lifting

Five of the included studies investigated movement variability during lifting tasks. Two of these studies (Fujii et al., 2022, Pranata et al., 2018) used a linear measure, specifically DP, while the remaining three studies (Bauer et al., 2015, Dideriksen et al., 2014, Moreno Catalá et al., 2018) utilised non-linear measures, including recurrence rate (REC), DET, and λmax (**Figure 2.3).**

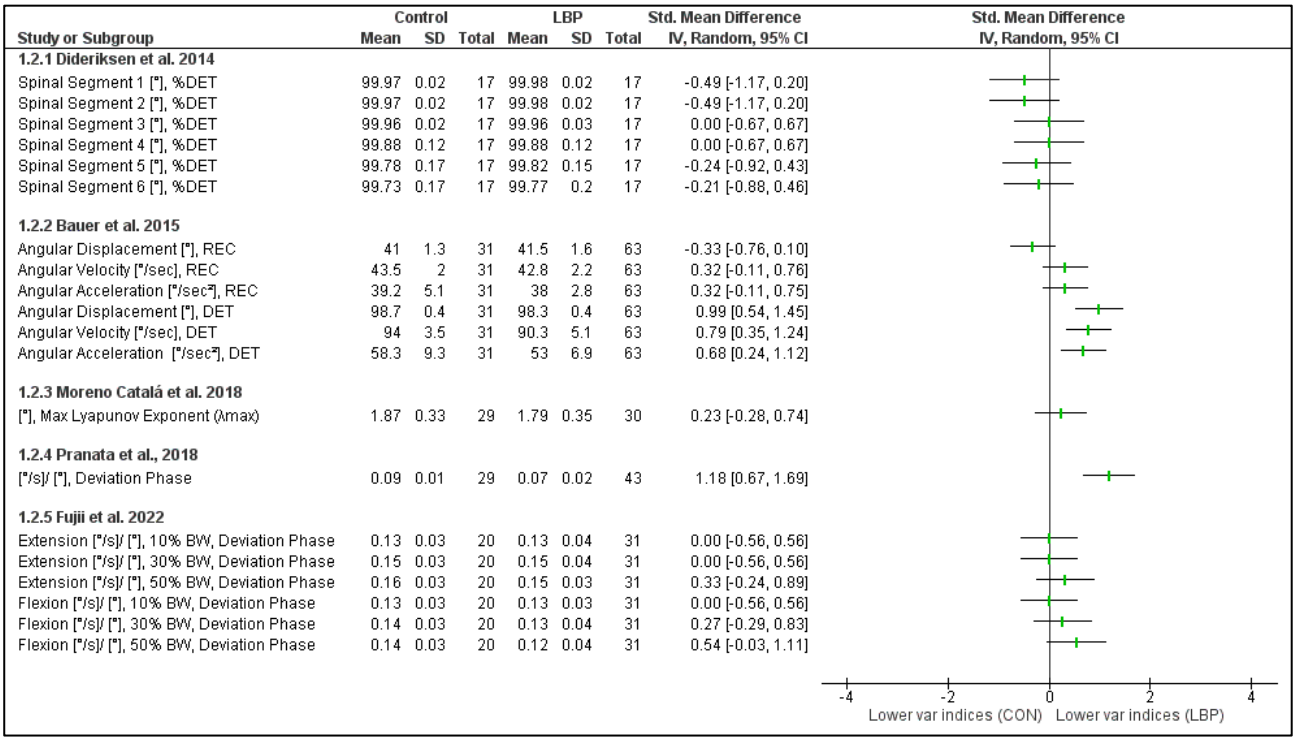


Figure 2.3: **Differences in movement variability between people with LBP and healthy controls (CON) while performing lifting tasks.**

DET: Determinism; REC: recurrence rate; Var: Variability.

All studies, apart from one (Bauer et al., 2015), did not show differences for people with LBP for movement variability during lifting. Bauer et al. (2015) showed less predictable lumbar movement patterns, as indicated by a significant reduction in determinism for various movement variables, including angular displacement, velocity, and acceleration.

Even though the forest plot in the study of Pranata et al. (2018) showed a significant effect (with a large size), the paper itself reported no effect for either subgroups recruited (i.e., LBP patients with low or high disability). This inconsistency between the forest plot results and the original study could be due to the statistical model's correction of variables for age effects. The same contrast was also obtained when LBP subgroups were compared separately with controls. In this case, people with LBP with low disability showed a significant effect. Overall, only one out of five studies reported a medium to large effect of the presence of LBP on movement variability during lifting tasks, characterised by a reduction in the predictability of lumbar movement.

Gait (walking and running)

Five studies included in this review used linear measures to quantify gait variability (**Figure 2.4).** One study (Vogt et al., 2001) used angular displacement, while the other four studies (Ebrahimi et al., 2017, Lamoth et al., 2006a, Lamoth et al., 2006b, Seay et al., 2011) used a combination of angular displacement and velocity as coordination indices, specifically the continuous relative Fourier phase (RP), continuous relative phase (SD RP).

All five included studies reported some differences in at least one of their outcomes, with four studies finding a decrease (Ebrahimi et al., 2017, Lamoth et al., 2006a, Lamoth et al., 2006b, Seay et al., 2011) and two finding an increase in variability of gait (during walking or running) (Lamoth et al., 2006b, Vogt et al., 2001). Even though the forest plot showed no effects in the study of Ebrahimi

et al. (2017), the original article reported a significant decrease in variability. The discrepancy could be due to the authors' use of a non-parametric test in their study since the data failed to fit a normal distribution. However, the most prominent finding was a decrease in variability of lumbar-pelvis coordination in the transverse plane and an increase in the frontal plane in those with LBP compared to controls regardless of walking speed (Lamoth et al., 2006a, Lamoth et al., 2006b). Overall, all studies reported a difference in movement variability in people with LBP compared to healthy controls, with effect sizes ranging from medium to large.

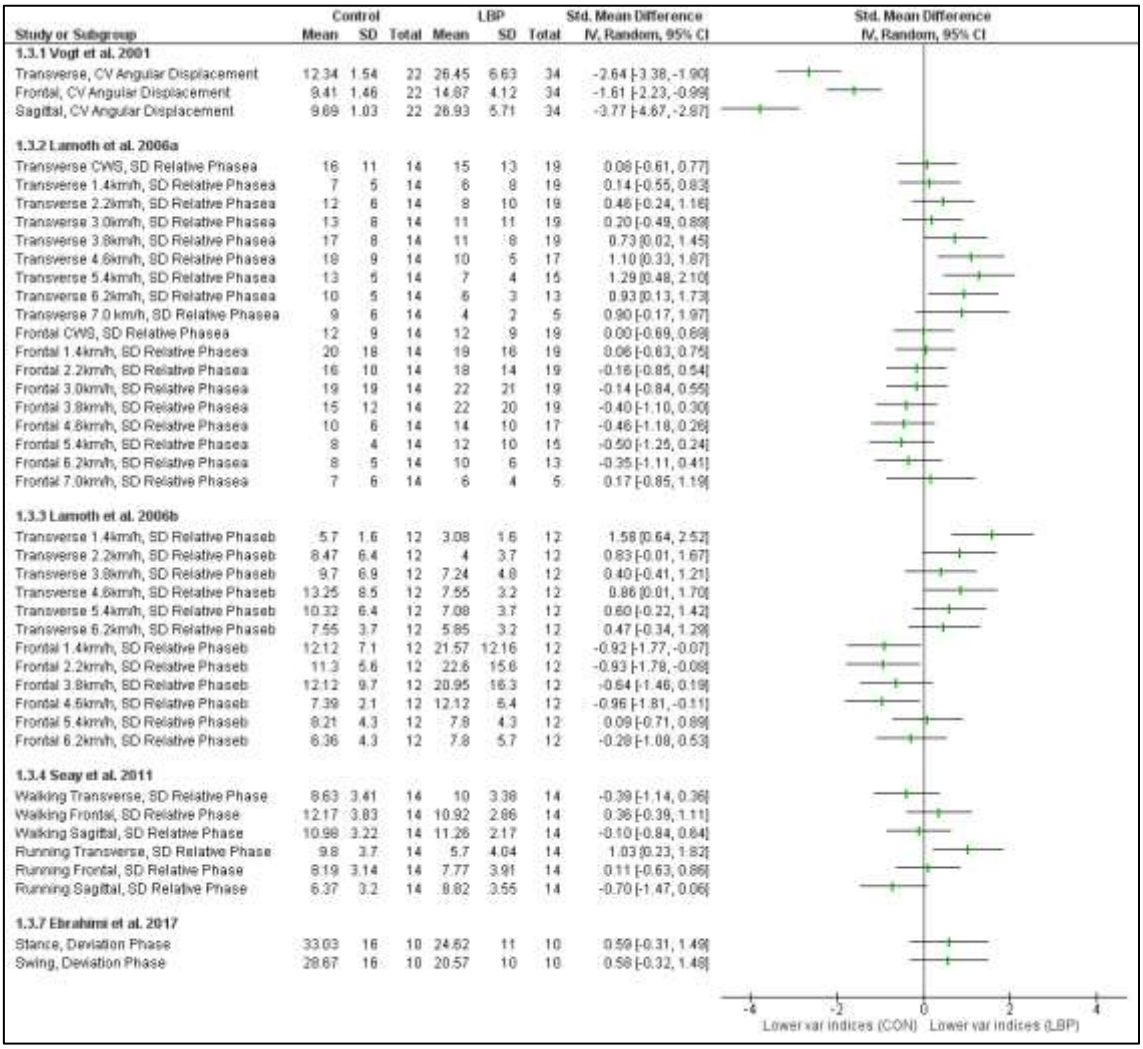


Figure 2.4: **Differences in movement variability between people with LBP and healthy controls (CON) during walking or running tasks.**

CV: Coefficient of Variation; SD: Standard deviation: Var: Variability.

Sit to stand to sit (STS) task

Only one of the included studies was categorised under this task (**Figure 2.5)**. This study investigated movement variability during a repeated sit-to-stand-to-sit (STS) task (Ippersiel et al., 2018), which divided the task into four periods: start, up, down, and end**.** The authors used DP to describe the amount of inter-joint coordination variability.

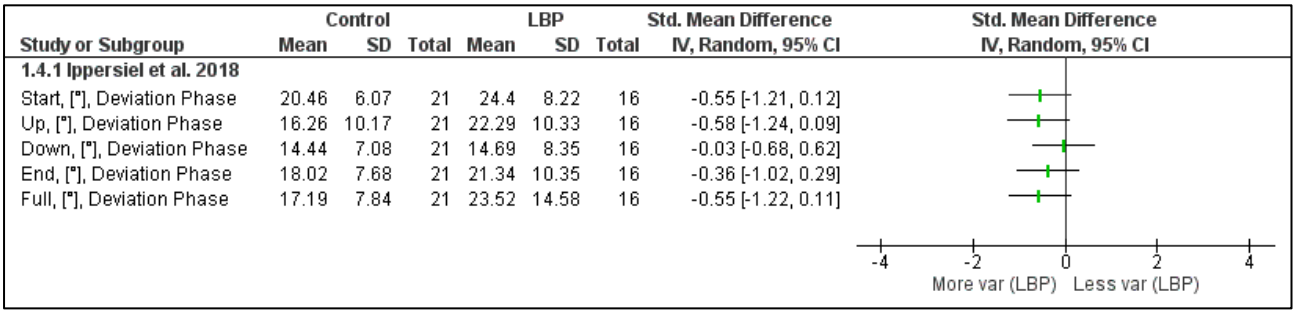


Figure 2.5: **Differences in movement variability between people with LBP and healthy controls (CON) during sit to stand task.**

SD: Standard deviation: Var: Variability.

For the lumbar region, no effect of LBP status was observed over the full task. However, there was a significant period effect characterised by greater variability over the start and end period of the STS task. No group or interaction effect was observed.

2.4.5 Methodological quality assessment

Five of the included studies (Bauer et al., 2017, Bauer et al., 2015, Dideriksen et al., 2014, Ippersiel et al., 2018, Mokhtarinia et al., 2016) were rated as high-quality studies that met most of the quality criteria (75% to 83%) (**Table 2.4)**. On the other hand, nine studies (Ebrahimi et al., 2017, Fujii et al., 2022, Graham et al., 2014, Lamoth et al., 2006a, Lamoth et al., 2006b, Moreno Catalá et al.,

2018, Pranata et al., 2018, Seay et al., 2011, Vogt et al., 2001) partially met the quality criteria (67%) and were rated as a moderate quality studies. The two most common weaknesses occurred in the report of the treatment history of those with LBP (item 6), and sample size justification or power description (item 12), and less commonly, representativeness of LBP and control groups (item 8).

Table 2.4: **Quality rating instrument using Modified Downs and Black Scale (adjusted specifically for the current review)**

Studies	***Item***												***Total /12***	***Percentage /100%***
	Reporting							***External validity***	***Internal validity/bias & confounding***			***Power***		
	1 *q.1 D &B*	**2** *q.2 D &B*	**3** *q.3 D& B*	**4 ***	**5 ***	**6 ***	**7** *q.7 D& B*	**8** *q.11 D&B*	**9** *q. 16 D & B*	**10** *q.20 D &B*	**11 ***	**12** *q.27 D&B*		
Graham et al. 2014 (Graham et al., 2014)	1	1	1	1	1	0	1	0	1	0	1	0	8	67
Mokhtarinia et al. 2016 (Mokhtarinia et al., 2016)	1	1	1	1	1	0	1	0	1	1	1	0	9	75
Bauer et al. 2017 (Bauer et al., 2017)	1	1	1	1	1	0	1	1	1	1	1	0	10	83
Dideriksen et al. 2014 (Dideriksen et al., 2014)	1	1	1	1	1	0	1	1	1	0	1	0	9	75

Bauer et al. 2015 (Bauer et al., 2015)	1	1	1	1	1	0	1	1	1	1	1	0	10	83
Moreno Catalá et al. 2018 (Moreno Catalá et al., 2018)	1	1	1	1	1	0	1	0	1	0	1	0	8	67
Pranata et al., 2018 (Pranata et al., 2018)	1	1	1	1	1	0	1	0	1	0	1	0	8	67
Fujii et al. 2022 (Fujii et al., 2022)	1	1	1	1	1	0	1	0	1	0	0	1	8	67
Vogt et al. 2001 (Vogt et al., 2001)	1	1	1	1	1	0	1	0	1	0	1	0	8	67
Lamoth et al. 2006a (Lamoth et al., 2006a)	1	1	1	1	1	0	1	0	1	0	0	1	8	67
Lamoth et al. 2006b (Lamoth et al., 2006b)	1	1	1	1	1	0	1	0	1	0	1	0	8	67
Seay JF et al. 2011(Seay et al., 2011)	1	1	1	1	1	0	1	0	1	0	1	0	8	67
Ebrahimi et al. 2017(Ebrahimi et al., 2017)	1	1	1	1	1	0	1	0	1	0	1	0	8	67
Ippersiel et al. 2018 (Ippersiel et al., 2018)	1	1	1	1	1	0	1	1	1	1	1	0	10	83

2.4.6 Level of evidence (GRADE)

The main outcome measures from individual studies were grouped per task type as domains and the obtained evidence was narratively described across studies. The quality of evidence per domain was summarised in accordance with GRADE and is reported in **Table 2.5**.

Table 2.5: **Quality of evidence assessment based on Grading of Recommendations, Assessment, Development and Evaluation (GRADE) criteria**

Movement variability based on the task performed	**Number of LBP patients (studies)**	**Risk of bias (D&B scale score)**	**Inconsistency**	**Indirectness**	**Imprecision**	**Number of participants**		**Publication bias**	**Overall Quality of Evidence**
						LBP group	**Control group**		
Repeated Flexion and Extension tasks	91 (3) Graham 2014 Mokhtarinia et al. 2016 Bauer et al. 2017	Not serious 67% 75% 83%	Not serious	Serious[b] ↓	Serious[c] ↓	10 22 59	10 22 27	Suspected[d]	Very low
Lifting tasks	184 (5) Dideriksen et al. 2014 Bauer et al. 2015 Moreno Catala et al. 2018 Pranata et al. 2018 Fujii et al. 2022	Not serious 75% 83% 67% 67% 67%	Serious[a] ↓	Serious[b] ↓	Serious[c] ↓	17 63 30 43 31	17 31 29 29 20	Suspected[d]	Very low

Gait	89 (5) Vogt et al. 2001 Lamoth et al. 2006a Lamoth et al. 2006b Seay et al. 2011 Ebrahimi et al. 2017	Not serious 67% 67% 67% 67% 67%	Serious[a] ↓	Serious[b] ↓	Serious[c] ↓	34 19 12 14 10	22 14 12 14 10	Suspected[d]	Very low
Sit to stand to sit (STS) task	16 (1) Ippersiel et al. 2018	Not serious 83%	Serious[a] ↓	NA*	Serious[c] ↓	16	21	Suspected[d]	Very low

GRADE: High quality: very confident that the true effect lies close to that of the estimate of the effect and further research is very unlikely to change. Moderate quality: moderately confident in the effect estimate and further research may change the estimate. Low quality: limited confident in the effect estimate and further research is very likely to have an important impact to change the estimate. Very low quality: Any estimate of effect is very uncertain.

[a] ↓High level of heterogeneity; we downgrade one level due to variability in results or inconsistency between effects.

[b] ↓Evidence was not directly comparable to the question of interest; we downgrade one level due to the variety of outcome measurement tools including the used motion analysis systems and the analysis metrics.

[c] ↓Few participants and few events: we downgrade one level due to the wide confidence interval (CI) around the estimate of the effect (as estimated by forest plot).

[d]Limited number of observational studies with small sample size as well as asymmetrical distribution of observations on the funnel plot

NA* not applicable: Only one study.

The overall quality of evidence was downgraded from low to very low for all domains mostly due to issues concerning imprecision of the included studies, inconsistency between effects, and to a lesser extent due to indirectness and potential publication bias. Downgrading the quality of evidence based on imprecision, was addressed using the optimal information size rule (OIS) to present the required sample size for the continuous outcomes that was used in the included studies. The usual standards

of α (0.05) and β (0.20), was used with an effect size of 0.2 SDs, representing a small effect, which required a total sample size of approximately 400 (200 per group) (Schünemann et al., 2008). However, the included studies had a maximum sample size of 94 participants, which suggests a small sample size, and resulted in a wide confidence interval (CI) around the estimate of the effect as detected by the forest plot. With regards to inconsistency, all domains showed serious concerns in heterogeneity of the results except for the repeated flexion and extension tasks that presented a significant overlap of confidence intervals as observed in the forest plot, suggesting minimal variation in effect sizes.

2.5 Discussion

This review is the first to provide a comprehensive analysis of observational studies that investigated whether thoraco-lumbar and lumbo-pelvic kinematic variability is different in people with CNSLBP compared to asymptomatic individuals, while performing repetitive cyclic functional tasks. As discussed in *Chapter One*, asymptomatic people typically exhibit a normal range of motor variability when performing functional tasks (Latash et al., 2002), however, those with LBP may display motor adaptations resulting in different movement variability compared with asymptomatic individuals (Brumagne et al., 2019). Movement variability is known to range from complete repeatability to excessive variability in both space and time (Harbourne and Stergiou, 2009). However, the degree of adaptive variability in the trunk during repetitive functional tasks among individuals with LBP is not well established which emphasises the need to synthesise the literature for a better understanding of the optimal adaptive variability for people with chronic LBP.

To facilitate interpretation, this review grouped the results into four categories based on the tasks used to investigate movement variability; repetitive trunk flexion and extension, lifting, gait, and in one study, sit-to-stand-to-sit. While the overall quality of evidence in this review was rated as very

low, due to the inclusion criteria of observational studies with small sample sizes, all included studies were of high to medium methodological quality, with no study rated as low quality. However, heterogeneity in the metrics used for analysis and effect sizes contributed to downgrade the quality of evidence.

Although this review sub-grouped the evidence for better interpretation, the choice of metrics within each group was crucial for understanding differences in movement variability. As mentioned previously, linear and non-linear metrics capture distinct aspects of movement variability that may vary independently from one another (Harbourne and Stergiou, 2009). For example, an increase in the structure of variability does not necessarily indicate an increase in the amount of variability. In the reviewed studies, differences in the structure of variability were commonly described using terms such as predictability or repeatability, rather than an increase or decrease in variability. Conversely, the amount of variability was typically reported simply an increase or decrease. This highlights the need for a nuanced approach to assess kinematic variability, where metrics such as the HA offers a comprehensive understanding of joint motion by capturing both amplitude and structural variability, thereby contributes to standardising terminology and facilitating clearer communication and interpretation of variability differences.

2.5.1 Differences in movement variability between people with and without chronic LBP

This review found that people with CNSLBP move their lumbar spine in a complex and less predictable way, likely as an adaptive response to pain, particularly noted as a difference in the angular velocity of the trunk during repetitive flexion and extension (Bauer et al., 2017, Graham et al., 2014, Mokhtarinia et al., 2016). Similarly, the task of lifting showed a general reduction in the predictability of angular displacement, velocity and acceleration (Bauer et al., 2015, Dideriksen et al., 2014, Fujii et al., 2022, Moreno Catalá et al., 2018, Pranata et al., 2018). Although this result was drawn from

non-linear metrics, for a comparable result, less predictable behaviour can be indirectly described as an increase in the amount of variability. The nature of both tasks similarly involves predetermined (i.e., loaded/unloaded, symmetrically/asymmetrically) repetitive trunk movements which resulted in people with LBP moving their lumbar spine in a more variable way. This finding is consistent with a previous review that found a common feature among individuals with chronic or mechanical LBP was increased kinematic spinal movement variability (Saito et al., 2021). Despite this consistency, these findings should be interpreted with caution due to the heterogeneity of the metrics used, which are conceptually different (Dijk et al., 2021). Moreover, the level of evidence supporting this observation is very low, indicating a lack of confidence in the estimate of this result.

Given that walking is one of the most common activities of daily living, numerous studies have examined motor variability during gait (Koch and Hänsel, 2019). Our review found that people with CNSLBP experience differences in kinematic variability compared to asymptomatic individuals during gait regardless of walking speed, which was primarily in coordination patterns of movement; however, the direction of difference was not consistent (Ebrahimi et al., 2017, Lamoth et al., 2006a, Lamoth et al., 2006b, Seay et al., 2011, Vogt et al., 2001). Gait studies typically investigate motor adaptations across multiple planes of movement, which provide a more comprehensive understanding of the direction of motor control changes. For instance, the reviewed studies reported more rigid and less variable coordination between transverse lumbo-pelvic rotations in people with LBP compared to healthy controls, whereas the coordination between spinal regions in the frontal plane was less rigid and more variable. This finding aligns with a previous review that found altered motor control in people with chronic LBP during gait, showing higher stride-to-stride kinematic variability. However, this was not surprising considering that most of the studies included in the previous review were also eligible for our review (Koch and Hänsel, 2018). The level of evidence was rated very low,

although the evidence was based on linear metrics of variability only, this was mostly due to the small sample sizes that led to wide CIs around the estimate of the effect.

There was limited evidence examining the sit-to-stand-to-sit task. However, similar to other tasks such as gait, the evidence was based on the amount of inter-joint coordination variability. Yet, no difference was observed in the adaptive variability during task performance between people with and without chronic LBP (Ippersiel et al., 2018).

2.5.2 LBP characteristics and movement variability

This review analysed 14 observational studies with a total of 380 participants with CNSLBP to determine the level of adaptive variability during various repetitive functional activities. Although the type of LBP was predetermined as chronic non-specific, there was no restrictions on LBP duration, intensity, or level of disability. However, the level of both LBP intensity and disability was minimal across studies, and some of the functional tasks may not have been challenging enough to evoke noticeable differences in movement variability. Although previous research has established an association between pain-related threat beliefs and disability with trunk kinematics in LBP people, a limited number of studies have investigated the impact of factors like fear-avoidance behaviour/beliefs and catastrophic thinking on kinematic variability (Shanbehzadeh et al., 2022). Only one study in the current review investigated the correlation between pain-related fear and trunk inter-joint coordination variability in people with chronic LBP (Fujii et al., 2022). Therefore, further studies are needed to explore the relationship between movement variability and pain-related psychological factors.

2.5.3 Methodological considerations

The current review adhered to rigorous methodology outlined in a predefined and published protocol (Alsubaie et al., 2021b). Screening, quality assessment, and data extraction was performed independently by two reviewers. In addition, unlike previous scoping reviews that did not assess the overall level of evidence (Dijk et al., 2021, Saito et al., 2021), the current review utilised GRADE to evaluate the overall level of evidence. Although meta-analysis was not applicable, we presented our findings quantitatively using forest plots to support the narrative synthesis.

There are some limitations that should be acknowledged. The current review included a limited number of observational studies with small sample sizes, which could have led to potential publication bias. Additionally, there are no established recommendations for evidence synthesis of observational studies, which makes it challenging to draw definitive conclusions based on the observational nature of the presented evidence (Mueller et al., 2018).

2.6 Conclusion

Despite very low level evidence, people with CNSLBP exhibited different motor adaptability compared with asymptomatic individuals, as indicated by differences in kinematic movement variability during repetitive functional tasks. However, the direction of these differences in movement variability was not consistent across individuals with chronic LBP. This systematic review highlights the importance of standardising terminology for assessing kinematic variability and emphasises the need for future research to consider the conceptual differences between different metrics.

CHAPTER 3

TRUNK CONTROL DURING REPETITIVE SAGITTAL MOVEMENTS FOLLOWING A REAL-TIME TRACKING TASK IN PEOPLE WITH CHRONIC LOW BACK PAIN

This chapter reports in full a manuscript which has been published previously (Alsubaie et al., 2021a). Changes have been made in the text of this chapter for the purposes of the thesis to reflect the content of previous chapters and to increase cohesion with studies in later chapters; specifically the used term ‘’ variability of the tracking accuracy’’ in the manuscript, have been replaced with the term ‘’kinematic variability’’ to better reflect the objectives of the current thesis. However, the majority of the text in this chapter reflects the published manuscript verbatim.

Publications and Presentations:

1. **Amal M. Alsubaie,** Eduardo Martinez-Valdes, Alessandro Marco De Nunzio, and Deborah Falla. 2021a. Trunk control during repetitive sagittal movements following a real-time tracking task in people with chronic low back pain, *Journal of Electromyography and Kinesiology*, 57, p.102533 **(Appendix 4)**
2. **Amal M. Alsubaie**, David Jiménez-Grande, and Alessandro Marco De Nunzio. Trunk coordination in people with low back pain during goal-directed repetitive sagittal trunk movements. The 11th Congress of the European Pain Federation (EFIC). Valencia, Spain, September 4 – 7, 2019.

3. **Amal M. Alsubaie**, David Jiménez-Grande, and Alessandro Marco De Nunzio. Trunk coordination in people with low back pain during goal-directed repetitive sagittal trunk movements. Physiotherapy UK conference, The Chartered Society of Physiotherapy. Birmingham, United Kingdom, November 1-2, 2019
4. **Amal M. Alsubaie**, Eduardo Martinez-Valdes, Alessandro Marco De Nunzio, and Deborah Falla. Trunk motor control during repetitive sagittal movements following a real-time tracking task in people with chronic low back pain. International Society of Electrophysiology and Kinesiology (ISEK). Virtual Congress, July 12-14, 2020.

3.1 Abstract

Motor control impairments in people with LBP could be attributed to deficits in lumbar proprioception and could potentially lead to poorer quality of movement. In the present study, we apply a novel real-time tracking task using a 3D motion capture system allowing participants to complete repetitive trunk motion, with the intention of assessing movement variability, and trunk motor control in general. Eleven asymptomatic volunteers and 15 participants with CNSLBP performed 12 continuous cycles of trunk flexion-extension following real time visual feedback, during which, trunk motion was measured using eight optoelectronic infrared cameras. Significant time differences between the feedback and actual trunk motion were found between groups (p=0.001). Both groups had similar kinematic variability when following the feedback (p>0.05). However, kinematic variability at a slow speed correlated (p=0.03; r=0.55) with the Fear-Avoidance Beliefs Questionnaire (FABQ) scores in those with CNSLBP. This study shows that movement variability over repeated tracking cycles was associated with the degree of fear of movement in people with CNSLBP. Additionally, both asymptomatic people and individuals with CNSLBP displayed anticipatory behaviour, however, the response of those with CNSLBP was consistently delayed in tracking the visual feedback compared to the asymptomatic group.

3.2 Introduction

Repetitive trunk movement represents an occupational risk factor since it can lead to cumulative spinal loading even when performed with no or minimal weight (Coenen et al., 2014). A further occupational risk factor is performing working tasks as quickly as possible, which is especially the case for self-paced work (Dempsey et al., 2010). Cumulative spinal loads from fast paced repetitive trunk movements can be associated with the development of LBP (Coenen et al., 2013).

As discussed in previous chapters and based on the results from *Chapter Two*, people with chronic LBP often present with impaired trunk motor control, which may contribute to the maintenance or perpetuation of their symptoms (Ghamkhar and Kahlaee, 2019, Sung et al., 2015). Motor control impairments in people with LBP could be, at least in part, attributed to deficits in lumbar proprioception (Lee et al., 2010, Tong et al., 2017). Indeed, it is expected that any proprioceptive impairment associated with LBP will affect the precise control of the trunk and could potentially lead to poorer quality of movement (Lee et al., 2010, Willigenburg et al., 2013).

Recently, movement variability based on kinematic measures has been employed as an index to assess the quality of movement within the context of active spinal motion (Alsultan et al., 2020). And since proprioceptive deficits are suggested to be more apparent during the performance of tracking or aiming tasks (Willigenburg et al., 2013). Thus, in the present study, we apply a novel real-time tracking task using a 3D motion capture system allowing participants to complete repetitive trunk motion, with the intention of assessing movement variability, while following visual feedback.

Therefore, the objective of this chapter was to explore trunk motor control while executing a tracking task to establish initial reference for the following chapters and offering a direction for further investigations. In the current chapter, we tested repetitive trunk flexion-extension

movements at varying speeds, with the aim of observing. 1. Kinematic variability during the tracking task, 2. Temporal difference between the feedback and actual trunk motion, and 3. Muscle activation and co-contraction in people with and without CNSLBP. A further objective was to assess for the presence of correlations between these outcome measures and levels of pain intensity, disability, and fear of movement in those with CNSLBP. Based on previous findings, our underlying assumption is that LBP people will tend to move slower with a stiffer trunk (Laird et al., 2019, van Dieën et al., 2003). Therefore, we hypothesised that people with LBP will show differences in movement variability, will be slower at tracking, and that they may present with greater co-contraction of their trunk muscles when performing repetitive tasks as a result of impairments in trunk motor control.

3.3 Methods

3.3.1 Design

This was a secondary analysis of an observational cross-sectional study conducted at the Centre of Precision Rehabilitation for Spinal Pain (CPR Spine), University of Birmingham, UK. Ethical approval for the study was granted by the Ethics Committee of the School of Sport, Exercise & Rehabilitation Sciences (CM 071217-1: **Appendix 5**) and the study was conducted according to the Declaration of Helsinki. All participants provided written informed consent. The study is reported in line with the STROBE guidelines (von Elm et al., 2008).

3.3.2 Participants

Eleven asymptomatic volunteers (8 men), and fifteen participants with CNSLBP (9 men) were enrolled in this study. Participants had to be between 18 and 55 years old and all individuals were

recruited from students and staff of the University of Birmingham and via the Spinal Pain Register of the CPR Spine. In line with previous comparable studies, a planned sample size of 28 participants was selected with 14 in each group, based on a previous study evaluated kinematic variability during repeated trunk flexion–extension movements (Asgari et al., 2015). The sample size was calculated using G*Power 3.1.9.4 based on α of 0.05, a power of 0.80, and a moderate effect size of (f) 0.23. Considering two groups being measured, 28 participants were needed to detect a significant effect. However, the original recruitment included 17 asymptomatic individuals and 15 with CNSLBP. Yet, not all participants' data were eligible for inclusion in this secondary analysis due to various factors, notably issues with markers reflection affecting the data quality of six asymptomatic individuals.

Asymptomatic participants were included in the study if they did not have back or lower limb pain/injury over the past three years that limited their functional abilities and/or which required treatment. People with CNSLBP were recruited if they had back pain that persisted for at least 3 months with pain experienced on at least half the days in the past 6 months (Dionne et al., 2008). People with LBP related to trauma, fractures, spinal stenosis, or radicular pain were excluded. They were also excluded if they were receiving active treatment for their LBP within the last 3 months. Participants from both groups were excluded if they had concurrent systemic disorders, a history of chronic respiratory or neurological problems, spinal deformity or surgery, cardiovascular conditions, and pregnancy.

3.3.3 Questionnaires

At the beginning of the session, the participants with LBP were asked to complete the following questionnaires to gather population statistics; The Oswestry Disability Index (ODI) questionnaire

was used which is a reliable measure of disability relating to back pain (Fairbank and Pynsent, 2000). The Fear-Avoidance Beliefs Questionnaire (FABQ) was used to asses any fear of movement related to pain using both physical activity (PA) and work (W) scales (Waddell et al., 1993). A general questionnaire was issued to assess LBP characteristics, including pain intensity over the past four weeks (Visual Analogue Scale, VAS, with 0-10 cm as anchor points for no pain and the worst pain imaginable, respectively) and duration of symptoms. Current pain intensity was also quantified at the time of testing on a VAS.

3.3.4 Movement analysis and electromyography

Trunk motion was acquired using eight optoelectronic infrared cameras with a resolution of 2,2 Mpixels (2048×1088pxs) (BTS SMART-Suite Motion Capture System by BTS Bioengineering, Italy). Seventeen spherical retroreflective markers (14mm) were used to construct 3D kinematic data of the trunk based on a modified model of markers' placement described previously to define seven trunk segments (Preuss and Popovic, 2010). Using double sided tape, markers were placed on the following anatomical landmarks which were identified by palpation to create two trunk segments; thoracic and lumbar segments (Sanderson et al., 2019): the modified model included two markers on the right and left acromion, posterior superior iliac spines (PSIS), anterior superior iliac spines (ASIS), and iliac crests (IC). In addition to unilateral markers on spinous processes of 3rd thoracic (T3), 3rd lumbar (L3). And bilateral markers to the spinous process of 7th cervical (C7), 6th thoracic (T6), 9th thoracic (T9), and 12th thoracic (T12).

Surface electromyography (sEMG) was acquired using a wireless sEMG system (BTS FREE EMG 1000, sampling rate 1000 Hz, bandwidth 10-500 Hz); signals were detected with single-differential sEMG probes (Ambu WhiteSensor Ag/Ag–Cl disks size: 36 mm x 40 mm). An inter-

electrode distance of 20 mm was chosen, following the SENIAM recommendations (Hermens et al., 2000). sEMG was acquired from the lumbar erector spinae (ES) and obliques externus abdominis muscles (OEA) bilaterally. The electrodes for OEA muscle were placed approximately 15 cm lateral to the umbilicus and for ES muscle 3 cm lateral to L3 spinous process (Radebold et al., 2000). Prior to the application of the electrodes, the skin was prepared by shaving the area if needed, applying an abrasive paste (SPES Medica, Italy) and finally cleaned with water.

3.3.5 Experimental procedure

Following placement of the reflective markers and sEMG electrodes, participants were seated with their arms crossed, and their hips and knees in 90^{o} flexion. They were instructed to sit in a neutral position. Subjects were instructed to position into an upright neutral spine position using a plumb line. The plumb line should be midway through the shoulder and lumbar spine.

A feedback signal was created in LabView software (National Instruments, USA) which displayed an oscillating vertical gauge with real-time visualisation of the actual trunk movement of the participant **(Figure 3.1)**. The real-time measure of the trunk motion was executed using the SMART ANALYZER suite (BTS Bioengineering, Milan, Italy) which was synchronised with the LabView software, in order to deliver the moving feedback gauge. Before execution of movement, the tracking system was calibrated.

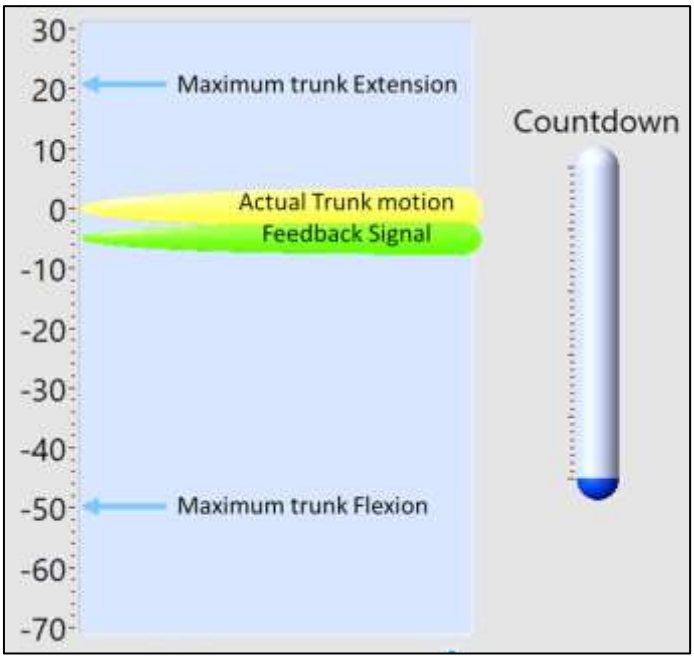


Figure 3.1: **Screenshot of the real-time feedback interface for the participants from the LabView software.**

The task consisted of 12 continuous cycles of 50^{o} trunk flexion and 20^{o} extension (full range) at two different speeds: 30^{o}/s (slow) and 50^{o}/s (fast) which were performed in a random order. Participants were instructed to move following the feedback into extension first to ensure better visualisation of the screen followed by trunk flexion which was then repeated for 12 continuous cycles. The real-time visual feedback was provided using a large screen approximately 60 cm in front of the participant. The screen was positioned according to the subjects' height so that they were able to see it clearly and move comfortably. No instructions were specified on how to look at the visual feedback (i.e. cervical and thoracic position). The screen was large enough to ensure the subject was able to see the visual feedback even at the end range of flexion or extension without constraining movement of cervical and thoracic spine. A maximum of three cycles of trunk flexion/extension were allowed as practice trials to familiarise participants with the task. The tracking system was calibrated again if the subject changed their posture during the acquisition.

3.3.6 Signal processing

Using BTS SMART software suite (SMART Tracker; BTS Bioengineering, Italy), data from the reflective markers were tracked and labelled using a custom kinematic model for the trunk so any errors in the tracking were corrected. Moreover, to facilitate comprehensive analysis of both kinematic and EMG data, a custom analysis protocol (SMART Analyzer) was created. This tool enabled the integration of kinematic and EMG data, allowing for synchronised analysis of movement trajectories and muscle activity patterns. Therefore, within the SMART Analyzer framework, the tracked markers were interpolated and smoothed using a triangular window with a filter of 20 Hz to reconstruct any missing kinematic data. EMG signals were band-pass filtered with cut-off frequencies between 20 Hz and 400 Hz (2^{nd} order Butterworth filter). These signals were then full-wave rectified and filtered again with a low-pass filter (2^{nd} order Butterworth filter) with a cut-off frequency of 5 Hz. Normalisation for the EMG data was conducted using a 300ms mean of the rectified envelope signal during the resting condition just before the movement initiation when the velocity was zero (Martinez-Valdes et al., 2019, Martinez-Valdes et al., 2016).

In order to quantify motion of the spine, the SMART Analyzer protocol was used to create separate reference coordinate systems for each segment with three axes (XYZ). The thoracic segment was defined by the markers on the right and left acromion, C7, T3, T6, T9, and T12 with the origin of the thoracic segment set to be at a virtual point mid-way between the two markers at the level of T6; the lumbar segment was defined by the markers on the PSIS, ASIS, IC, and L3 with the origin of the lumbar segment set from the marker at L3 to monitor movement of the spine **(Figure 3.2).** In addition, to a global reference system matching the laboratory orientation used as a fixed reference system. The angular displacement of the mid-thoracic and lumbar segments were measured separately in degrees using Euler angles in relation to the fixed global reference system. The decision to measure trunk angles in the global frame of reference was made to ensure a

consistent reference point for comparisons across different repetitions, especially when providing feedback over multiple cycles of trunk movements.

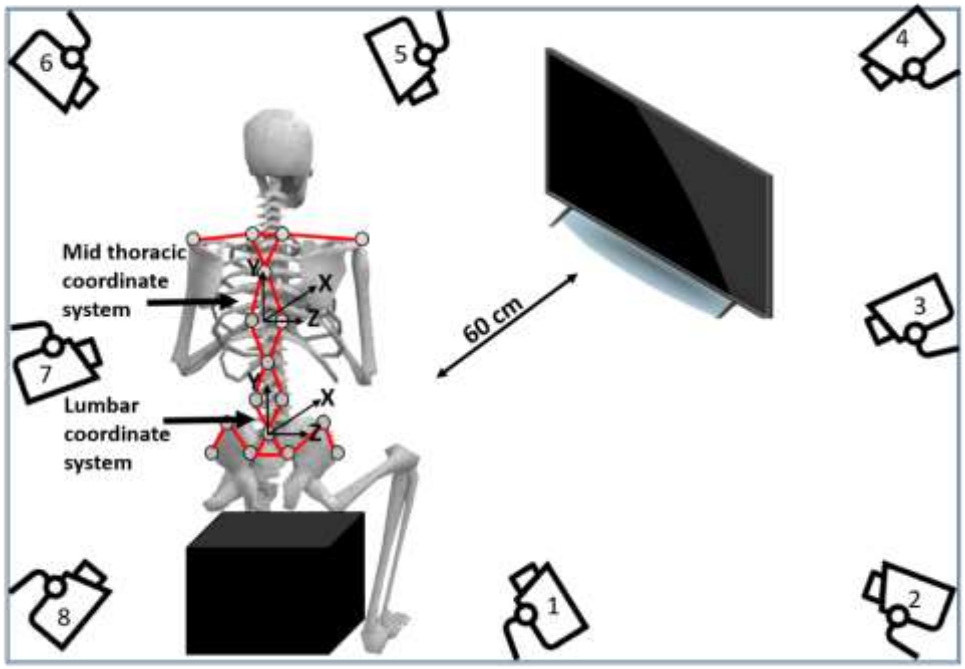


Figure 3.2: **The laboratory setup using 8 infrared cameras and 17 reflective markers with the coordinate system created for the mid-thoracic and lumbar regions**

In order to evaluate the kinematic variability during the tracking task, the twelve continuous cycles of angular displacements were divided into 12 separate cycles and plotted against each other. Each cycle was time normalised to 101 samples (0-100% of cycle time). Point-by-point standard deviations (SD) were computed across all cycles then averaged to measure the mean of SD (MeanSD) **(Figure 3.3).** This was calculated for each participant to quantify movement variability for lumbar and mid-thoracic spine segment (Asgari et al., 2015).

A custom made MATLAB code R2019a (The Mathworks, Natick, United States) was used to perform a cross correlation analysis in order to observe the similarity between the feedback signal and the actual trunk movement with the aim of detecting any temporal difference between the two signals in terms of e.g., anticipating or lagging relative to the feedback signal. The sample lag that was detected between the two signals was converted into time lag in seconds.

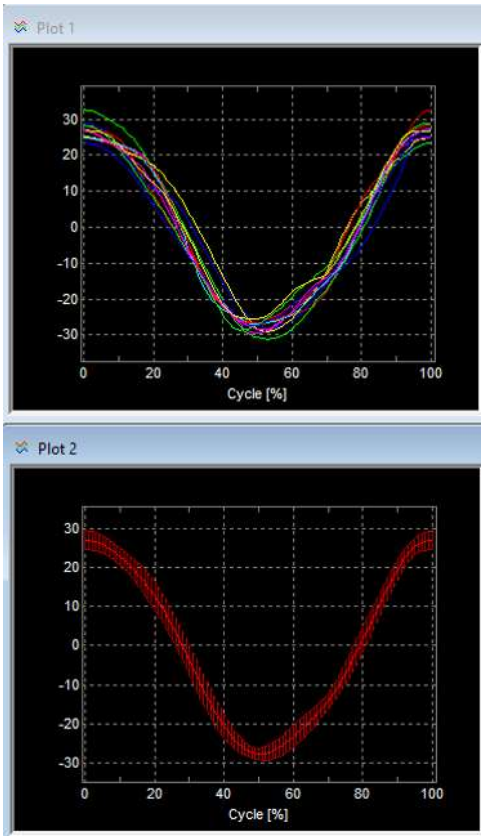


Figure 3.3: **Thoracic angular displacement displayed for one participant showing how the kinematic variability during tracking task was quantified.**

Plot.1 illustrates the 12 cycles plotted against each other; whereas **Plot.2** illustrates the point by point standard deviation and mean of the measured angular displacement for each cycle.

The normalised EMG signals were used to define a co-contraction index (CCI) between trunk flexors and extensors. The normalised EMG amplitude of lumbar erector spinae (nES) and obliques externus abdominis muscle (nOEA) were used in the following formula where ES was nominated as the agonistic muscle and OEA as the antagonistic (Kiewiet et al., 2017, Knarr et al., 2012):

$$\text{Co-contraction Index (\%)} = 2x\left(\frac{\text{nOEA}}{\text{nOEA+nES}}\right)x100$$

A CCI of 100% indicates a comparable activation of the normalised antagonistic and agonistic EMG amplitude.

3.3.7 Statistical analysis

Normal distribution of the data was confirmed using a Shapiro–Wilk test. A Two-way Mixed Analysis of Variance (ANOVA) was conducted to detect any significant differences between the two groups in terms of kinematic variability during tracking, temporal difference, and trunk muscle activation with between subject factor, group (control vs. LBP) and a within-subject factor, speed (slow vs. fast)

Pearson correlation was used to evaluate associations between kinematic variability and EMG variables with questionnaires scores' for the LBP group including; ODI, FABQ-PA, FABQ-W, and VAS scores at the time of testing and over the past four weeks. SPSS Version 25 (IBM Corp., Armonk, NY, USA) was used for all statistical analyses and statistical significance was set at $p < 0.05$.

3.4 Results

Eleven asymptomatic volunteers and fifteen participants with LBP successfully completed data collection **(Table 3.1)**. LBP group presented with minimal disability level and pain at the time of testing. There were no significant differences in the demographic characteristics between groups, with no differences identified in the mean age, height nor body mass index.

Table 3.1: **Participant characteristics (mean ± SD)**

	Healthy (n = 11)	**LBP (n = 15)**	***p*-value**
Age (years)	31.45 ± 4.25	37.06 ± 9.13	*p*= 0.072
Height (m)	1.70 ± 0.06	1.71 ± 0.05	*p*= 0.791
Body mass (kg)	66.00 ± 10.25	73.46 ± 8.60	*p*= 0.055
ODI (%)	-	10.8 ± 6.7	
Pain VAS	-	1.9 ± 2.1	
Average pain of the most recent episode	-	5.7 ±2.1	
Actual Pain	-	2.1 ±1.6	
Last 24 hours Pain	-	2.3 ± 1.7	
Worst pain previous month	-	5.2 ± 2.7	
FABQ-W	-	9.1 ± 8	
FABQ-PA	-	13.5 ± 4.4	

3.4.1 Kinematic variability during tracking task

No significant main effect of group (F (1, 24)=1.90, p=0.181, ηp^2 =0.073) was observed for the movement variability of the lumbar segment regardless of the movement speed (F (1, 24)=0.535, p=0.472, ηp^2 =0.022) **(Figure 3.4)**; the LBP group had similar kinematic variability (fast speed= 3.61°±1.18°; slow speed= 4.17°±1.56°) compared to the control group (fast speed= 3.38°±1.02°; slow speed= 3.16°±1.14°). There was no significant interaction between group and speed (F (1, 24) = 2.94, p=0.099, ηp^2 =0.109).

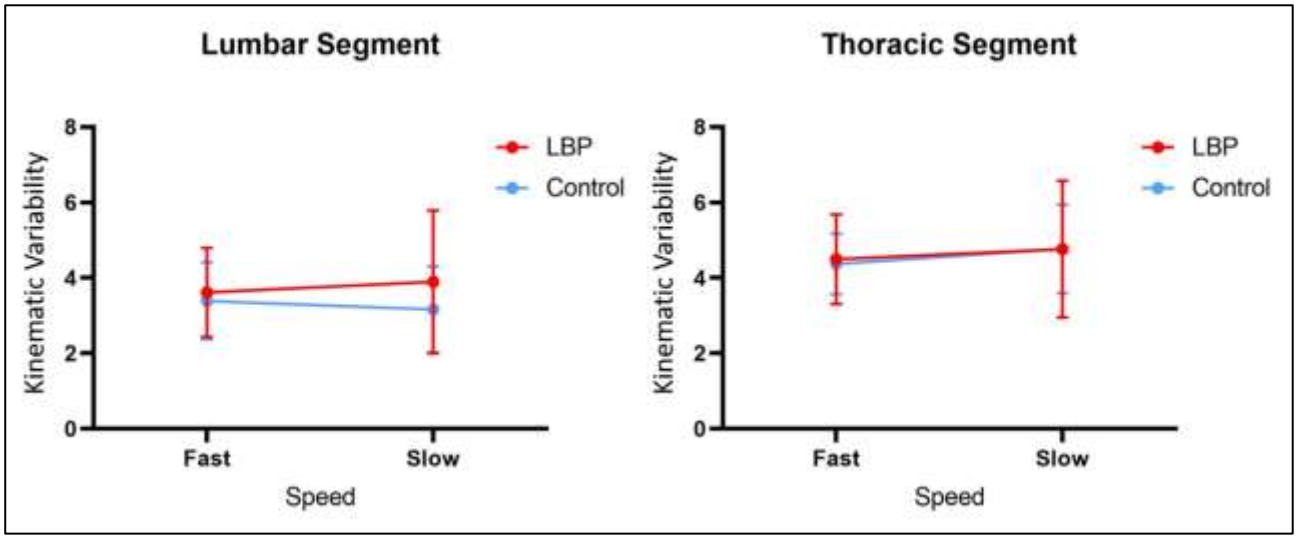


Figure 3.4: **Mean and SD of the kinematic variability in asymptomatic people (controls) and people with low back pain (LBP).**

The kinematic variability of the thoracic segment did not differ significantly between groups (F (1, 24) = 0.382, p=0.542, ηp^2 =0.016). In addition, there was no significant main effect of speed (F (1, 24) = 4.15, p=0.053, ηp^2 =0.148) on the kinematic variability of the thoracic segment **(Figure 3.4);** However, there was no significant interaction between group and speed (F (1, 24) = 1.69, p=0.685, ηp^2 =0.007).

A significant (p=0.03; r=0.55) moderate positive linear correlation was found between the kinematic variability of the lumbar segment during the slow speed task and the FABQ-PA score **(Figure 3.5)**. A FABQ-PA higher score indicates more strongly held fear avoidance beliefs. This was not the case for the kinematic variability of the lumbar segment during the fast speed task (p=0.08; r=0.46) nor for the thoracic spine segment during either the fast (p=0.149; r=0.39) nor slow (p=0.366; r=0.25) speed tasks. Apart from this result there were no other significant correlations between the outcome measures and levels of pain and disability in the LBP group.

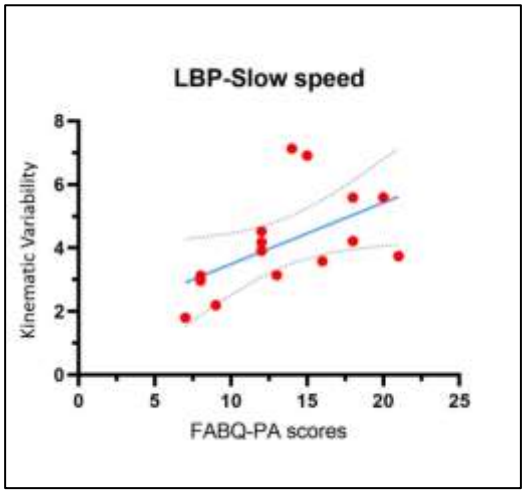


Figure 3.5: **The relationship between kinematic variability of the lumbar spine and the FABQ-PA scores.**

3.4.2 Temporal difference between the feedback and actual trunk motion

The ANOVA revealed a significant main effect of group ($F(1, 24) = 15.9$, $p=0.001$, $\eta p^2 =0.399$) for the temporal difference. The control group were anticipating the feedback by 0.54±0.55 s in the faster task and by 0.75±0.78 s in the slower task whereas the LBP group anticipated the feedback in the faster task by 0.10±0.54 s and in the slower task their motion was delayed relative to the feedback signal by 0.19±0.32 s **(Figure 3.6).**

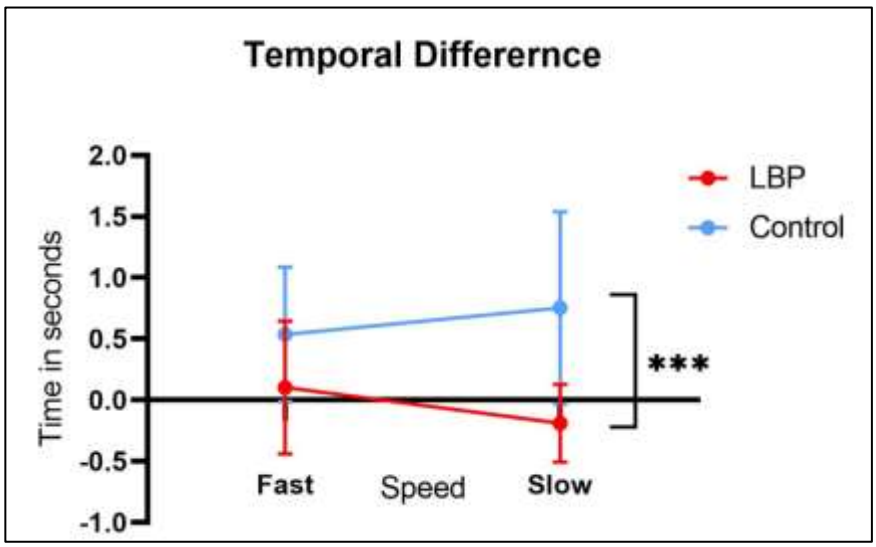


Figure 3.6: **Mean and SD of the temporal difference between the feedback signal and the actual trunk movement for asymptomatic people (controls) and people with low back pain (LBP).** A **positive value** implies anticipation of the feedback signal whereas a negative value implies a delay relative to the feedback signal***: $\boldsymbol{p \leq 0.001}$.

In contrast, there was no significant main effect of speed on the temporal difference (F (1, 24) = 0.074, p=0.787, ηp^2 =0.003), with participants showing similar time lag or anticipation when performing the task at different speeds. In addition, there was no significant interaction effect between group and speed (F (1, 24) = 3.50, p=0.073, ηp^2 =0.127).

3.4.3 Muscle activity and co-contraction index

The CCI as well as the individual amplitude of ES and OEA activity did not differ significantly (p >0.05) between LBP and asymptomatic groups in either task. However, there was a significant main effect of speed (F (1, 24) = 15.8, p=0.001, ηp^2 =0.397) with greater OEA activity during the faster task in both groups **(Table 3.2).** Finally, there was no significant interaction effect between group and speed for muscle activity.

Table 3.2: **Mean and SD of muscles activity and CCI for each group and task ***:$p \leq 0.001$**

Group	Speed	Lumbar erector spinae	Obliques externus abdominis muscles	Co-contraction index CCI (%)
Control	Fast	1.40 ± 0.65	2.71 ± 1.51 ***	120.7 ± 21.8
	Slow	1.28 ± 0.53	1.88 ± 0.7 1	114.7 ± 20.6
LBP	Fast	1.40 ± 0.50	2.45 ± 0.85 ***	120.1 ± 16.8
	Slow	1.53 ± 1.10	1.96 ± 0.72	113.3 ± 21.0

3.5 Discussion

We evaluated trunk motor control using a novel 3D real-time tracking task while varying the speed of motion. The movement variability of thoracic and lumbar motion didn't differ between groups over repeated cycles of the tracking task, however, the degree of lumbar motion variability during the slow speed task was significantly associated with the degree of fear of movement in those with CNSLBP. In addition, asymptomatic people were able to anticipate the feedback signal when the task was performed at a slow or fast speed whereas the temporal difference between the feedback signal and the actual movement of the trunk was less in people with CNSLBP and even became delayed when the task was performed at a slow speed. In contrast with our hypothesis, no difference in the degree of co-contraction of the trunk flexors and extensors was observed between groups.

The kinematic variability, in the current study, during the tracking task may be considered as a measure of spatial error independent of timing error to test trunk motor control (Newell et al., 1994). Therefore, it could be suitable to compare the current results to the previously founded results on tracking error rather than movement variability. Our findings did not identify the presence of greater error in the CNSLBP group in terms of spatial parameters (i.e., ROM in

degrees) when following the feedback. However, previous studies have shown proprioceptive disturbances in people with LBP detected with 3D motion capture (Hidalgo et al., 2013, Sheeran et al., 2012). Yet, these previous studies used repositioning error to quantify lumbar proprioceptive control. These differences in findings suggest that feedback tracking tasks may place different demands on proprioceptive processing and motor adaptation mechanisms compared to repositioning tasks. Therefore, future studies could explore how these task-specific differences influence spinal kinematic variability and contribute to understanding motor control changes in individuals with CNSLBP.

Interestingly, a moderate linear correlation was found between the kinematic variability of lumbar spine motion during the slow speed task and the FABQ-PA score, which may indicate reduced ability of the participants with higher fear of movement to predict the parameters needed to perform the underlying motor task (Schmidt, 2003). Other reports indicate that people with LBP and high fear of movement tend to move slower and with a stiffer trunk (Karayannis et al., 2013, Osumi et al., 2019). This may explain why the significant correlation between movement variability and fear was only observed during the slow speed task. However, no significant correlations were reported in the present study between the movement variability and pain intensity or disability.

Motor adaptation and learning are two fundamental processes for the flexibility of normal motor control (Bastian, 2008). Although, both groups showed anticipatory motor adaptive behaviour at least during the faster movements, the response of those with CNSLBP was delayed in comparison to the control group. A delayed motor behaviour in people with LBP has been attributed previously to slower initiation of motion at the pelvis resulting in greater delay at the onset of flexion when performing both functional and non-functional dynamic tasks (Claeys et al., 2012, Laird et al., 2019). Individuals with CNSLBP might seem to be closer to the feedback signal, suggesting better tracking compared to controls. However, this interpretation warrants caution, as it could be

influenced by unexplored factors such as proprioceptive disturbances, pain perception, or other underlying differences in motor control strategies between the two groups. Therefore, while individuals with CNSLBP exhibit delayed motor behaviour, further investigation is needed to fully understand the complexities underlying their tracking abilities relative to controls.

In the current study, we did not identify a difference in the level of trunk muscle co-contraction between groups, although this has been observed in some studies investigating trunk muscle activity in LBP (van Dieën et al., 2003), there is also a number of studies which has not identified such differences (Arvanitidis et al., 2021, Martinez-Valdes et al., 2019, Mueller et al., 2017, Mueller et al., 2020). Nevertheless, the difference in task performance implies different muscle strategy based on other features of the EMG signal (e.g., temporal and spatial features) could reveal differences between groups (Falla et al., 2014, Mueller et al., 2017, Sanderson et al., 2019). Moreover, it is possible that the activity of other muscles, not recorded, differed between groups.

Although there was no effect of group on the activation pattern of the muscles, there was a significant effect of speed on the activation of the OEA muscle with higher activity at faster speeds, an observation confirmed previously (Vera-Garcia et al., 2008) which is possibly a strategy to stiffen the trunk as the task speed increases (Zoppirolli et al., 2017).

3.5.1 Methodological considerations

Instantaneous feedback of muscle activation intensity using EMG biofeedback has been commonly applied in research and clinical practice. In contrast, feedback on kinematics is less utilised likely due to the technical difficulties in assessing and quantifying these outcomes quickly and accurately (Hunt, 2013). In the present study, we were able to provide such feedback despite these difficulties that may affect the accuracy of the results. A further issue is that the present study

was limited to performing non-functional repeated trunk movements, which may not reflect actual dynamic activities of daily living. Finally, the participant sample size as well as the reported low levels of pain and disability may lack sensitivity to detect smaller effects. Thus, further studies with larger sample size and people with higher level of LBP are recommended for recruitment to improve generalisability of data.

3.6 Conclusion

In conclusion, the extent of the variability of lumbar spine motion in people with LBP was associated with the degree of fear of movement when the tracking task was performed at a slow speed. Additionally, they showed a delay relative to asymptomatic participants in tracking real-time feedback of trunk motion. Collectively, this study provides new insights into how trunk motor control is modified in people with LBP.

CHAPTER 4

SPINAL KINEMATIC VARIABILITY IS INCREASED IN PEOPLE WITH CHRONIC LOW BACK PAIN DURING A REPETITIVE LIFTING TASK

This chapter presents the full contents of a published manuscript (Alsubaie et al., 2023b). It incorporates the original manuscript along with modifications made specifically for this thesis.

Publications and Presentations:

1. **Amal M. Alsubaie,** Andy Sanderson, Hélio V. Cabral, Eduardo Martinez-Valdes, and Deborah Falla. 2023b. Spinal kinematic variability is increased in people with chronic low back pain during a repetitive lifting task, *Journal of Electromyography and Kinesiology*, 73, p.102832. **(Appendix 6)**
2. **Amal M. Alsubaie,** Andy Sanderson, Hélio V. Cabral, Eduardo Martinez-Valdes, and Deborah Falla. Spinal kinematic variability is increased in people with chronic low back pain during a repetitive lifting task. UK Sensorimotor Conference. Newcastle, United Kingdom, June 26-28, 2023.

4.1 Abstract

Differences in spinal kinematic variability have been observed in people with CNSLBP compared with asymptomatic individuals during the performance of various repetitive functional tasks. However, the direction of these differences (i.e., less or more kinematic variability) is still not established. This study aimed to assess differences in kinematic variability of the 3D angular displacement of thoracic and lumbar spinal segments in people with CNSLBP compared to asymptomatic individuals during a repetitive lifting task to resemble a more functional activity. Eleven people with CNSLBP and eleven asymptomatic volunteers performed 10 cycles of multi-planar lifting movements while spinal kinematics were recorded. For the three planes of motion, point-by-point standard deviations (SDs) were computed across all cycles of lifting and the average was calculated as a measure of kinematic variability for both segments. People with CNSLBP displayed higher thoracic (F= 8.00, p=0.010, ηp^2=0.286) and lumbar kinematic variability (F= 5.48, p=0.030, ηp^2=0.215) in the sagittal plane. Moreover, group differences were observed in the transversal plane for thoracic (F= 7.62, p=0.012, ηp^2=0.276) and lumbar kinematic variability (F= 5.402, p=0.031, ηp^2=0.213), as well as in the frontal plane for thoracic (F= 7.27, p=0.014, ηp^2=0.267) and lumbar kinematic variability (F= 6.11, p=0.022, ηp^2=0.234) all showing higher variability in those with CNSLBP. A significant main effect of group (p<0.05) was not detected for spinal ROM. Interestingly, people with CNSLBP completed the lifting task with the same ROM in all three planes of motion as observed for asymptomatic individuals, yet they performed the lifting task with higher spinal kinematic cycle-to-cycle variation.

4.2 Introduction

In addition to the revealed results in *Chapter Three*, alterations in trunk movement patterns have been observed previously in people with LBP, however, the underlying mechanisms behind these motor control changes remains poorly understood (Hodges and Tucker, 2011, van Dieën et al., 2019b). Numerous studies have extensively studied trunk movement patterns and trunk muscle activity in an attempt to understand strategies of trunk motor control in association with LBP (van Dieën et al., 2019b). One of the well-established strategies of motor adaptation to LBP, as reported in *Chapter One and Chapter Two*, are changes in spine kinematics as well as changes in the variability of these kinematic variables (Gizzi et al., 2019, Hodges and Smeets, 2015, Vaisy et al., 2015, van Dieën et al., 2017). Although we hypothesised, in the previous chapter, that tracking task might be sensitive in detecting differences in trunk motor control between asymptomatic individuals and people with CNSLBP, however, no differences were revealed in term of kinematic variability. That was attributed to executing the repetitive trunk movements in a non-functional manner, which does not reflect actual dynamic activities of daily living.

Kinematic variability is crucial when performing activities of daily living with high repeatability as well as in occupational settings (Abboud et al., 2014). Repetitive lifting is one of the common functional tasks that has a possible reported causative role in LBP development and has frequently been investigated to better understand potential injury risks and strategies to improve lifting performance (Abdoli-Eramaki et al., 2019). Yet, the majority of these studies aimed to explore lift-to-lift variability to understand the physical demands of the task in healthy individuals in order to optimise ergonomics (Oomen et al., 2023a, Oomen et al., 2023b, Tetteh and Mirka, 2018, Tetteh and Mirka, 2021). The quantitative analysis of such inherent motor control variability during trunk repetitive movements was frequently driven from linear measures of spine kinematics such as ROM, velocity or acceleration. Differences in kinematic variability among people with LBP has

also been observed as aberrant movement patterns when patients are asked to perform active trunk movements in different planes of motion during the physical examination (Biely et al., 2014, Gombatto et al., 2007, Marich et al., 2020). These quantitative and qualitative analyses of kinematic features suggest inconsistent intra-individual movement variability when people with CNSLBP execute repetitive trunk movements (Dijk et al., 2021, Wattananon et al., 2023).

A limited number of studies have explored kinematic variability during repetitive lifting in people with CNSLBP (Asgari et al., 2017, Bauer et al., 2015, Dideriksen et al., 2014, Fujii et al., 2022, Moreno Catalá et al., 2018, Pranata et al., 2018). One study identified that the variability of lumbar movement patterns, in terms of angular displacement, was different in those with greater LBP intensity as they performed a repetitive lifting task (Bauer et al., 2015). However, most of the studies have explored coordination variability during repetitive lifting tasks in one plane of motion (trunk flexion and extension) and they have failed to identify different kinematic variability patterns in people with CNSLBP compared to asymptomatic individuals (Asgari et al., 2017, Fujii et al., 2022, Pranata et al., 2018).

Therefore, the purpose of the study in this chapter was to assess differences in kinematic variability of 3D angular displacement of two spine segments (thoracic and lumbar) in people with CNSLBP compared to asymptomatic individuals as they perform a cyclic lifting task executed in a multi-planar pattern with the intention to reflect a more functional task. Moreover, to explore the clinical characteristics of those with CNSLBP. We hypothesised that people with CNSLBP would present with differences in trunk motor control strategies revealed as differences in spinal kinematic variability given the more complex and multi-planar nature of the lifting task.

4.3 Methods

This was a secondary analysis of an observational study, conducted at the Centre of Precision Rehabilitation for Spinal Pain (CPR Spine) in the University of Birmingham. Ethical approval for the study was granted by the University Ethics Committee (Approval number: ERN_16-1389B: **Appendix 7**), and the study was conducted according to the Declaration of Helsinki. All participants provided written informed consent. The study is reported in line with the STROBE guidelines (von Elm et al., 2008).

4.3.1 Participants

Twenty-two volunteers (men and women) aged 18-65 years were recruited from the student and staff community of the University of Birmingham, UK via poster and social media advertisements. An a-priori sample size calculation was completed as described in *Chapter Three*, with the same minimum sample of 28 identified based on α of 0.05, a power of 0.80, a moderate effect size of (f) 0.23. However, although 15 asymptomatic individuals and 14 with CNSLBP were initially recruited, not all participant data met the criteria for inclusion in this secondary analysis. This was mainly due to factors like the inability to complete all necessary movement cycles required for calculating kinematic variability, resulting in the exclusion of data from four asymptomatic individuals and three with CNSLBP.

Participants with CNSLBP had similar inclusion and exclusion criteria used in previous *Chapter Three*. Age and BMI matched control participants were recruited and had to have no history of low back or lower limb pain which warranted attention from a healthcare practitioner. Participants from both groups were excluded if they were on high doses of anti-inflammatories (>30mg morphine

equivalent dose), pregnant, or were experiencing any concurrent systemic, rheumatic or neuro-musculoskeletal disorders which could confound testing.

4.3.2 Questionnaires

Baseline characteristics of participants were assessed by questionnaires prior to data collection. Anthropometric data were recorded at the beginning of the session. For the LBP participants, a bespoke back pain questionnaire was used to collect information on their LBP history and intensity which was assessed using a Pain Numeric Rating Scale (PNRS) (Breivik et al., 2008). In addition, participants from both groups were required to complete several similar questionnaires used in *Chapter Three* including back disability assessed using ODI (Fairbank and Pynsent, 2000), and their beliefs and fears about movement related to pain assessed by the FABQ (Waddell et al., 1993). Moreover, recent activity levels were assessed by the International Physical Activity Questionnaire (IPAQ) (Craig et al., 2003) and recent mental health by the Depression, Anxiety and Stress Scale (DASS-21) (Henry and Crawford, 2005, Lovibond and Lovibond, 1995). General health at the time of data collection was assessed using the SF-36 (V2) (Walsh et al., 2003). Finally, the Borg Rating of Perceived Exertion (RPE) scale was used to measure the exertion rate after the performance of the lifting task (Borg, 1998).

4.3.3 Lifting task

The task consisted of a repetitive loaded lifting task between six shelves positioned in front and to the sides of the participant. In order to reduce the load on the low back during task performance, ergonomic interventions were applied individually for each participant by adjusting the location and

height of each shelf based on their anthropometry (Faber et al., 2007). Using adjustable shelves and palatable anatomical landmarks, the height and positions of shelves were determined (**Figure 4.1**).

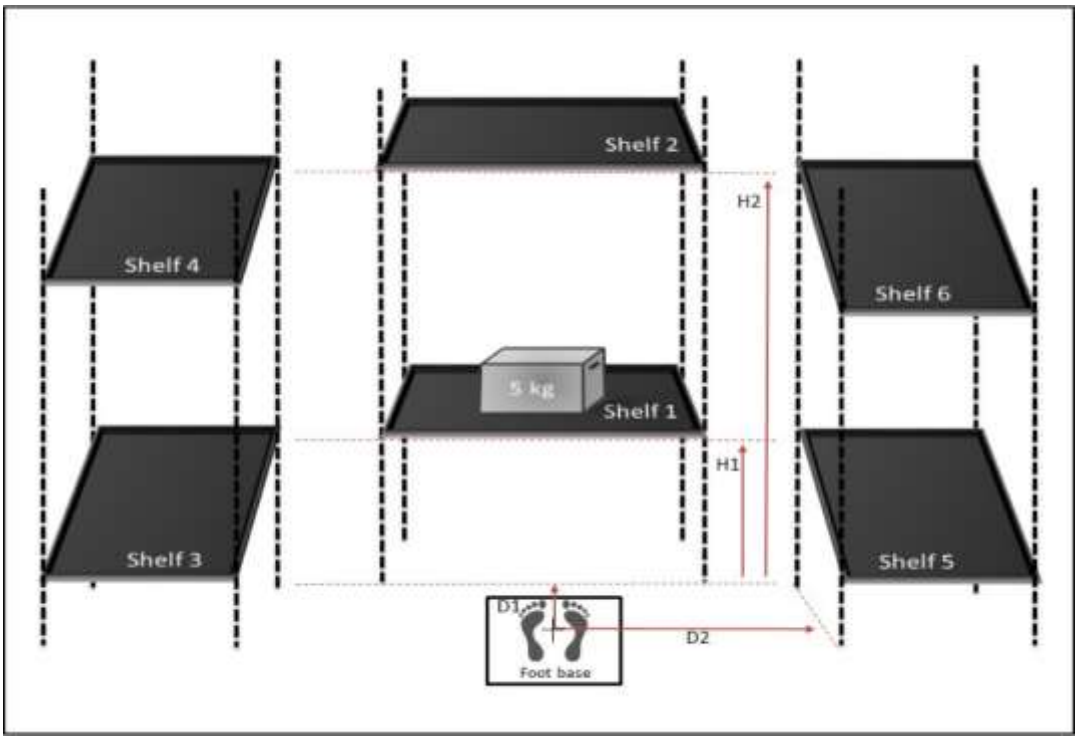


Figure 4.1: **Illustration of the experimental set-up**

Showing the six adjustable shelves and the distance of the shelves from the foot-base which is located half-way between the two olecranon processes when the arms are abducted 90°; **D1:** the distance from acromion process to the ulnar styloid process when the arms are flexed 90°; **D2:** from the foot-base to the olecranon processes when the arms are abducted 90°. **H1:** the height of the lower shelves to the lateral femoral epicondyle height; **H2** the height of the upper shelves to manubriosternal angle height.

To reflect a daily living task of lifting, the participants were asked to repetitively lift a standardised weight (5kg) (35.5cmx29cmx13.5cm) in a multi-planar pattern of movement between the six shelves. The weight was standardised to ensure consistency and comparability among participants, while the choice of a 5kg weight was based on it being considered manageable yet challenging enough to elicit physical exertion. 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). From the standing position, participants performed 10 cycles of lifting. Specifically, the lifting task required the participant to move the box from the lower shelf-1 (S1) to a sequential shelf (e.g., S2), and then return to the starting position on S1, before moving to the next sequential shelf (i.e., S3, S4, S5, and S6), with rest between movements. Thus, S1 was identified as the start and the end of each lifting movement. For example, moving from S1 to S5 then back to S1 was defined as one complete lifting movement. In total, each participant completed 10 cycles of 5 lifting movements (i.e., S1-S2-S1,…, S1-S6-S1). In order to control the speed, the rhythm of the task was controlled by a metronome (30 beats per minute) with 2 seconds allocated to each lifting movement followed by a rest of 2 seconds. Participants were asked to not move their feet during lifting and to try to limit knee movement, but no further instructions were given regarding the lifting technique.

Before starting, the task was explained by researchers using standardised instructions, and a demonstration of one complete cycle was given. Participants were then allowed to practise one complete timed cycle with an unweighted box to ensure that the pattern and lifting technique at the knees and feet were performed as instructed. The task was completed in one continuous acquisition lasting approximately 7minutes in total. Following task completion, participants were asked to rate their perceived effort using the RPE scale.

4.3.4 Motion capture

3D movements of the trunk were captured using eight infrared cameras (BTS Bioengineering, Milan, Italy). The kinematic data was acquired at a frequency of 250Hz following system calibration. A modified version of a previously described kinematic trunk model was used (Müller et al., 2016). Ten reflective markers (14mm) were placed with double-sided tape over the

anatomical landmarks as illustrated in **Figure 4.2** in order to define two spinal segments. The markers were placed in triangular patterns overlying the spine to facilitate division of the spinal regions into segments (**Figure 4.2**). Reflective markers were also placed on the box, and the distal edge of each shelf (S1-S6).

However, it's important to note that variations in the marker sets exist across different chapters within this thesis. These differences were primarily due to the secondary analyses conducted in *Chapters Three* and *Four*, which limited our options based on the available data. Despite these variations, our methodology maintained consistency in terms of creating and analysing the spine segments using a triangular pattern model to ensure comparability across analyses.

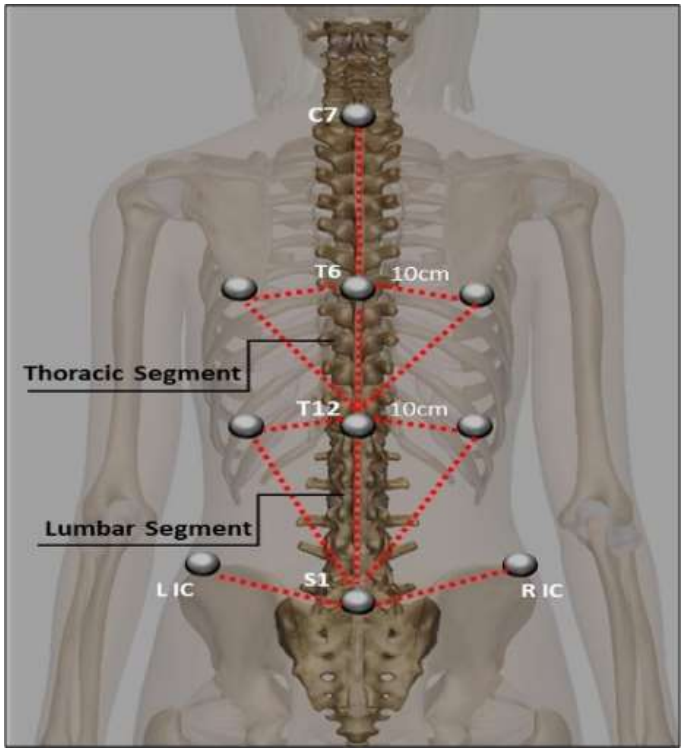


Figure 4.2: **Markers placement and segmentation for the spine kinematic model**
The markers were adhered to the skin overlying 7th cervical vertebra (**C7)**, 6th thoracic vertebra **(T6)**, 12th thoracic vertebra (**T12**) and 1st sacral vertebra (**S1**), right iliac crest (**R IC**) and left iliac crest (**L IC**).

4.3.5 Processing of 3D kinematic data

Using BTS SMART software suite (SMART Tracker& Analyzer; BTS Bioengineering, Italy), data from the reflective markers were tracked and labelled using a custom kinematic model for the trunk. Data were then processed using Matlab (R2022a, MathWorks, Natick, MA, USA). First, the 3D kinematic data obtained during the repetitive lifting task were interpolated and smoothed using a 2^{nd} order Butterworth low-pass filter with a cut-off frequency of 5Hz (Sanderson et al., 2019). Then, the fifty continuous cycles (5 cycles x 10 times each) were divided into 50 separate trials using the markers positioned on the six shelves and the displacement of the marker placed on the box.

Utilising the varying distances between the markers on the box and those on each shelf, movements to and from each shelf were accurately reconstructed. Subsequently, the 3D movement tracks were divided into individual cycles, each corresponding to a single lifting movement between shelves. Subsequently, each cycle was time-normalised to obtain 101 samples per cycle (0-100% of cycle time) (Asgari et al., 2015).

The markers along the subject's spine were divided into a group of four markers in triangular patterns to define the two spine segments (**Figure 4.2**). The thoracic segment (TS) was defined by the markers on T12, T6 and 10cm lateral to T6; the lumbar segment (LS) was defined by the markers on the S1, T12 and 10cm lateral to T12. A Cartesian axis system was created for each spine segment. In addition to the global coordinate system of the laboratory, a local coordinate system was defined at the pelvis level using three markers on the S1 and right and left iliac crest. Spinal angular displacement was expressed as the relative Euler angle of the movement of each spine segment with respect to the adjacent segment below, with the thoracic segment being relative to the lumbar segment and the lumbar segment relative to the pelvis. Specifically, the relative angle of the thoracic segment was calculated relative to the lumbar segment, and the relative angle of the lumbar segment was calculated relative to the pelvis. The 3D rotation angles were calculated using an X-Z-

Y (Frontal - Sagittal - Transverse) Cardan sequence **(Figure 4.3)** (Cotter et al., 2014, Needham et al., 2016, Preuss and Popovic, 2010).

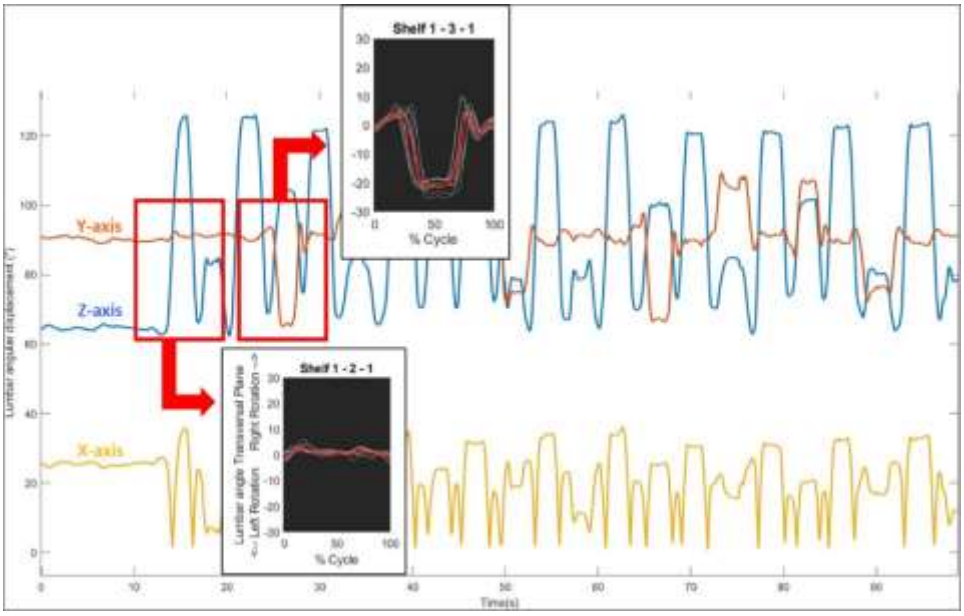


Figure 4.3: **An example outcome of lumbar angular displacements measured in three planes of motion (XYZ); (x-axis): Frontal, (z-axis): Sagittal, (y-axis): Transversal.**

In addition, an example is presented of an extracted measure of kinematic variability as MeanSDs from the first and second lifting movements from transversal plane.

To analyse the ROM during lifting movements, the angular displacement of each spinal segment has been measured as participants moved from the starting position (S1) to each subsequent shelf in three planes of motion in order to quantify the ROM achieved by each participant, even within the defined constraints of shelf positions and levels.

To quantify the kinematic variability of the spine angular displacement (thoracic, lumbar), point-by-point standard deviations (SDs) were computed across all 10 cycles for the five lifting movements in three planes of motions then averaged to measure the MeanSDs **(Figure 4.3)** (Asgari et al., 2015).

4.3.6 Statistical analysis

Normal distribution of the data was confirmed using a Shapiro–Wilk test and thus parametric tests were applied. Independent t-tests were used to compare differences in anthropometric data and clinical characteristics between groups. Separately for each plane of motion, two-way mixed Analysis of Variance (ANOVA) were conducted to compare main and interaction effects of group (control vs. CNSLBP; between subject factor), and shelves (S1-S2-S1,…, S1-S6-S1; within-subject factor) on thoracic and lumbar kinematic variability (MeanSDs). Whenever main effects were identified by ANOVA, Bonferroni post-hoc test was used for pairwise comparisons. The same analysis was also performed to assess spinal ROM (i.e., thoracic and lumbar angular displacement). Effect sizes were reported where appropriate with ANOVA results, in the form of ηp^2 values (Lakens, 2013). Statistical analysis was performed using SPSS 29 (IBM, USA) with an alpha level set at $\alpha = 0.05$. All results are expressed as mean and standard deviation (Mean±SD).

4.4 Results

Participants' characteristics are presented in **Table 4.1**. No significant anthropometric differences were found between groups for age nor BMI ($P>0.05$). The CNSLBP group reported mild current LBP intensity of 2.82/10 (±2.04), minimal disability level on the ODI (15.59±7.82%) and reported moderate exertion after the task on the Borg scale (12.55 ±1.80). As expected, those with CNSLBP presented with significantly higher degrees of back disability, fear of movement, and greater perceived exertion compared with asymptomatic individuals.

Table 4.1: **Participant anthropometrics and questionnaires' results (data presented as Mean±SD)**

BMI: body mass index, **IPAQ:** International Physical Activity Questionnaire, **ODI**: Oswestry Disability Index, **PNRS:** Pain Numeric Rating Scale, **FABQ:** Fear Avoidance Beliefs Questionnaire, **DASS-21:** Depression, Anxiety and Stress Scale, **RPE:** Borg Rating of Perceived Exertion, **CNSLBP:** chronic non-specific low back pain. ***p*<0.05; ****p*< 0.005; **** *p*< 0.001

	Control group (N=11; ♂: 4, ♀ 7)	**CNSLBP group (N=11; ♂: 5, ♀ 6)**	**P-value Two-sided**
Age (years)	24.27±4.62	25.82±8.32	*P*=0.597
BMI (kg/m^2)	23.34±4.71	25.17±3.28	*P*=0.304
IPAQ	83.33% High	83.33% High	-
SF-36 General Health	58.89±2.04	49.38±4.54	*P<0.001***
ODI (%)	0.36±1.20%	15.59±7.82	*P<0.001***
Current PNRS	0	2.82±2.04	*P<0.001***
Last 24hrs PNRS	0	3.82±2.18	*P<0.001***
Average PNRS	0	5.32±2.05	*P<0.001***
FABQ- total	1.91±4.11	26.73±11.55	*P<0.001***
DASS-21	9.82±9.22	23.09±28.83	*P*=0.161
BORG (RPE) Scale	10.82±1.83	12.55±1.80	*P*=0.038*

Based on the measured relative angles of spinal segments, there was no significant main effect of group for the range of thoracic angular displacement in the sagittal plane while performing the lifting movement (F= 1.34, p=0.260, ηp^2=0.063). However, there was a main effect of shelf (F= 13.83, p<0.001, ηp^2=0.40), but no interaction effect between group and shelf (F= 2.03, p=0.140, ηp^2=0.092). In addition, there was also no significant main effect for group on the range of lumbar angular displacement in the sagittal plane (F= 0.98, p=0.332, ηp^2=0.047). Moreover, there was a main effect of shelf (F= 18.84, p<0.001, ηp^2=0.40), however, no interaction effect between group and shelf (F= 0.19, p=0.843, ηp^2=0.009).

In the transversal plane, there was no significant main effect of group on the range of thoracic angular displacement during the lifting movement (F= 2.88, p=0.105, ηp^2=0.126). However, there was again a main effect of shelf (F= 8.14, p=0.005, ηp^2=0.28), but no interaction effect between group and shelf (F= 0.37, p=0.594, ηp^2=0.019). In addition, there was no significant main effect of

group on the range of lumbar angular displacement in the transversal plane during the lifting movement (F= 0.74, p=0.397, ηp^2=0.036). Moreover, there was no main effect of shelf (F= 2.94, p=0.064, ηp^2=0.128), nor interaction effect between group and shelf (F= 2.13, p=0.131, ηp^2=0.097).

In the frontal plane, there was no significant main effect of group on the range of thoracic angular displacement while performing the lifting movements (F= 1.91, p=0.182, ηp^2=0.087). There was also no main effect of shelf (F= 1.85, p=0.163, ηp^2=0.085) or an interaction effect between group and shelf (F= 1.22, p=0.307, ηp^2=0.058). Furthermore, there was no significant main effect of group on the range of lumbar angular displacement in the frontal plane during the lifting movement (F= 3.27, p=0.085, ηp^2=0.141). However, there was a main effect of shelf (F= 13.4, p<0.001, ηp^2=0.401); but no interaction effect between group and shelf (F= 2.38, p=0.093, ηp^2=0.124).

The range of angular displacement based on relative angles for each segment are presented in **Table 4.2** in degrees of motion (°) and are expressed as Mean±SD.

Table 4.2: **Range of motion (ROM°) of thoracic and lumbar segments in three planes of motion while performing the lifting task based on relative angles.**

SD: Standard Deviation: **TS:** thoracic segment, **LS:** lumbar segment, **S1-2:** shelf1 to shelf2,

Spinal segment: lifting movement	Group	ROM (°)	
		Mean	SD
SAGITTAL PLANE			
TS: S1-2	Control	25.7076	23.79404
	CNSLBP	40.4448	30.34752
TS: S1-3	Control	35.2604	26.19830
	LBP	36.1412	22.00213
TS: S1-4	Control	24.6175	22.16953
	LBP	37.2505	28.97142
TS: S1-5	Control	9.6917	9.94578
	LBP	24.0107	22.65711
TS: S1-6	Control	27.6501	23.37993
	LBP	41.9509	30.28087
LS: S1-2	Control	24.1168	21.49180
	CNSLBP	34.1504	24.19698
LS: S1-3	Control	16.1412	12.86101

	LBP	23.8328	17.01420
LS: S1-4	Control	19.0390	17.03051
	LBP	26.8556	22.07910
LS: S1-5	Control	15.4389	14.54993
	LBP	22.7258	17.49828
LS: S1-6	Control	30.2190	23.26092
	LBP	36.9345	22.67231
TRANSVERSAL PLANE			
TS: S1-2	Control	.9683	.98345
	CNSLBP	2.0167	2.70154
TS: S1-3	Control	8.4676	7.15455
	LBP	17.5623	20.45796
TS: S1-4	Control	1.8536	1.73907
	LBP	3.3260	3.54669
TS: S1-5	Control	17.6183	20.53886
	LBP	20.1340	23.32670
TS: S1-6	Control	2.5131	1.51985
	LBP	4.9295	2.79128
LS: S1-2	Control	1.2955	1.17631
	CNSLBP	1.6796	1.75091
LS: S1-3	Control	2.8687	2.16165
	LBP	7.8367	8.59439
LS: S1-4	Control	8.7878	9.53290
	LBP	5.9735	9.55615
LS: S1-5	Control	8.5365	10.50324
	LBP	6.4309	4.31799
LS: S1-6	Control	2.7626	1.98506
	LBP	9.1921	9.77465
FRONTAL PLANE			
TS: S1-2	Control	1.4515	.89976
	CNSLBP	.3187	.40559
TS: S1-3	Control	1.5263	1.00950
	LBP	1.6917	1.72632
TS: S1-4	Control	1.8074	1.36744
	LBP	1.5620	1.11343
TS: S1-5	Control	1.5833	1.31127
	LBP	1.4447	1.56585
TS: S1-6	Control	1.6872	1.45466
	LBP	.9116	.77797
LS: S1-2	Control	2.8065	1.74536
	CNSLBP	3.6037	2.85834
LS: S1-3	Control	1.9131	2.58310
	LBP	2.3729	2.77053
LS: S1-4	Control	4.5378	2.90925
	LBP	11.3994	9.29414
LS: S1-5	Control	1.1377	.94547

	LBP	1.1069	1.46266
LS: S1-6	Control	5.3744	5.64915
	LBP	10.3013	8.82721

4.4.1 Differences in kinematic variability

Sagittal plane

For the thoracic segment, there was a significant main effect of group showing that people with CNSLBP displayed higher thoracic kinematic variability (F= 8.00, p=0.010, ηp^2=0.286) compared with healthy controls, independent of the five lifting movements. Thoracic kinematic variability for the CNSLBP group was 6.29°±0.70(SE), whereas for the healthy controls it was 3.48°±0.70(SE) with a mean difference of 2.81° and 95% confidence interval (95%CI)=0.645, 2.23. In addition, there was a significant main effect for shelf (F= 13.25, p<0.001, ηp^2=0.39); thoracic kinematic variability was found to be higher for movements to the lower shelves (S3, S5) compared with the upper shelves (S4, 5, 6) (Bonferroni post-hoc results are shown in **Table 4.3**). Nevertheless, no interaction effect was observed between group and shelf (F= 2.66, p=0.095, ηp^2=0.118) (**Figure 4.4**).

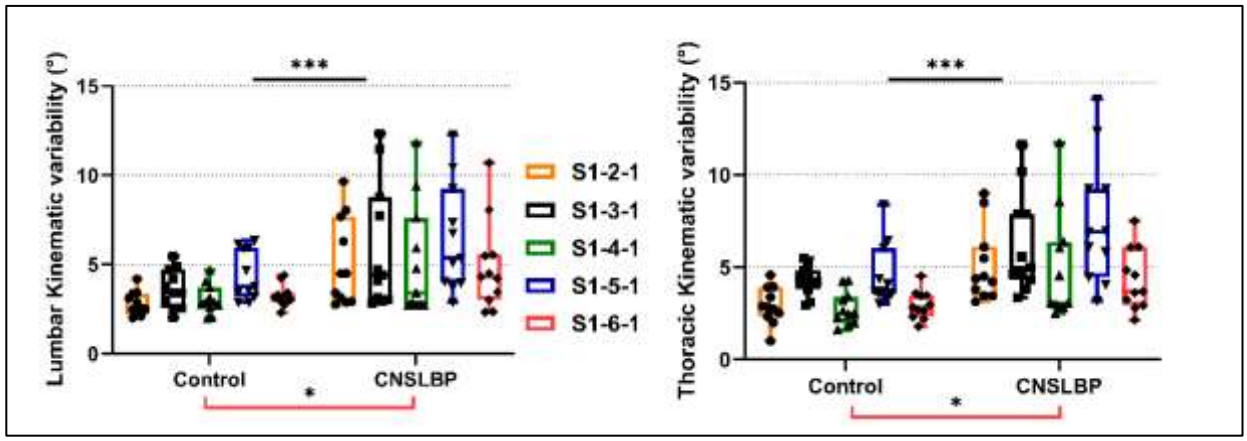


Figure 4.4: **Thoracic and lumbar kinematic variability differences between people with CNSLBP and healthy controls in the Sagittal plane of motion**

Box plot displays the range from minimum to maximum values, with individual data points shown; **S1-2-1:** shelf1 to shelf2 to shelf1. The lower line represent the statistically significant main effect of group, the upper line represent the statistically significant main effect of shelf: ***p*<0.05; ****p*< 0.005; ***** *p*< 0.001

For the lumbar segment, there was a significant main effect for group and people with CNSLBP had greater lumbar kinematic variability (F= 5.48, p=0.030, ηp^2=0.215) compared with healthy controls, independent of the five lifting movements. Lumbar kinematic variability for the CNSLBP group was 5.69°±0.68(SE), whereas for the healthy controls it was 3.43°±0.68(SE) with a mean difference of 2.25° and 95%CI=0.246, 4.267. There was a significant main effect of shelf (F= 14.51, p<0.001, ηp^2=0.42); lumbar kinematic variability was found to be higher for movements to the lower shelves (S3, S5) compared with the upper shelves (S4, 5, 6) (Bonferroni post-hoc results are shown in **Table 4.3**). However, no group by shelf interaction effect was observed for lumbar kinematic variability (F= 1.10, p=0.346, ηp^2=0.052) (**Figure 4.4**).

Transverse plane

For thoracic segment, there was a significant main effect of group revealing that people with CNSLBP showed higher thoracic kinematic variability (F= 7.62, p=0.012, ηp^2=0.276) compared with healthy controls. Thoracic kinematic variability for the CNSLBP group was 5.96°±0.73(SE), whereas for the healthy controls it was 3.08°±0.73(SE) with a mean difference of 2.87° and 95%CI=0.702, 5.043. Moreover, there was a significant main effect of shelf (F= 22.41, p<0.001, ηp^2=0.52); thoracic kinematic variability was found to be higher for movements to the lower shelves (S3, S5) (Bonferroni post-hoc results are shown in **Table 4.3**). In addition, there was also an interaction effect observed between group and shelf, with only the CNSLBP group showing a significant difference of thoracic kinematic variability with the lifting movements (F= 5.60, p=0.011, ηp^2=0.219) (**Figure 4.5**).

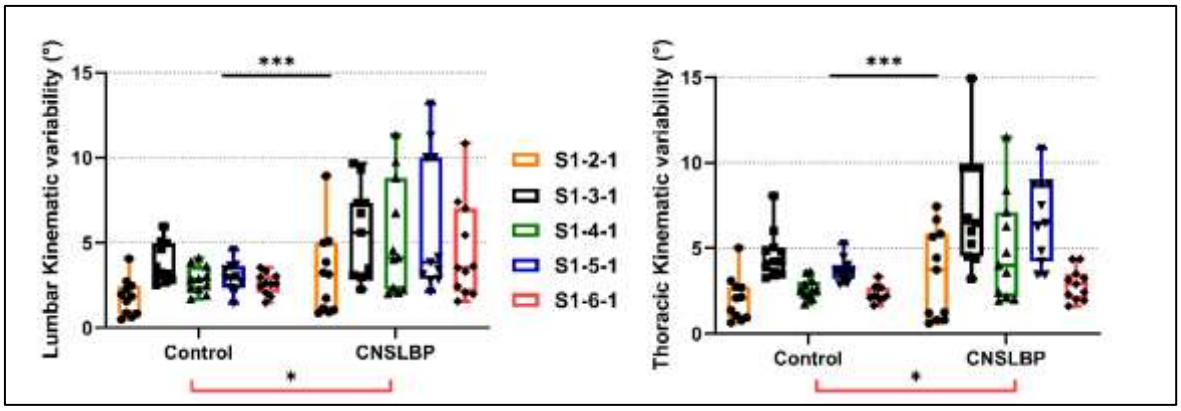


Figure 4.5: **Thoracic and lumbar kinematic variability differences between people with CNSLBP and healthy controls in the Transversal plane of motion**

Box plot displays the range from minimum to maximum values, with individual data points shown; **S1-2-1:** shelf1 to shelf2 to shelf1. The lower line represent the statistically significant main effect of group, the upper line represent the statistically significant main effect of shelf: ***p*<0.05; ****p*< 0.005; ***** p*< 0.001

For the lumbar segment, there was a significant main effect of group; people with CNSLBP displayed greater lumbar kinematic variability (F= 5.402, p=0.031, ηp^2=0.213) compared with healthy controls, independent of the five lifting movements. Lumbar kinematic variability for the CNSLBP group was 5.28°±0.75(SE), whereas for the healthy controls it was 2.80°±0.75(SE) with a mean difference of 2.47° and 95%CI=0.254, 4.692. In addition, there was a significant main effect of shelf (F= 14.67, p<0.001, ηp^2=0.42); lumbar kinematic variability was found to be higher for movements to the lower shelves (S3, S5) (Bonferroni post-hoc results are shown in **Table 4.3**). However, no group by shelf interaction effect was observed for lumbar kinematic variability (F= 2.12, p=0.122, ηp^2=0.096) (**Figure 4.5**).

Frontal plane

For the thoracic segment, there was a significant main effect for group revealing that people with CNSLBP showed higher thoracic kinematic variability (F= 7.27, p=0.014, ηp^2=0.267) compared with healthy controls. Thoracic kinematic variability for the CNSLBP group was 7.06°±0.79(SE), whereas for the healthy controls it was 4.03°±0.79(SE) with a mean difference of 3.02° and 95%CI=0.686, 5.364. Moreover, there was a significant main effect of shelf (F= 24.43, p<0.001, ηp^2=0.55); thoracic kinematic variability was found to be higher for movements to the lower shelves (S3, S5) compared with the upper shelves (S4, 5, 6) (Bonferroni post-hoc results are shown in **Table 4.3**). In addition, there was also a group by shelf interaction effect (F= 3.61, p=0.049, ηp^2=0.153) (**Figure 4.6**).

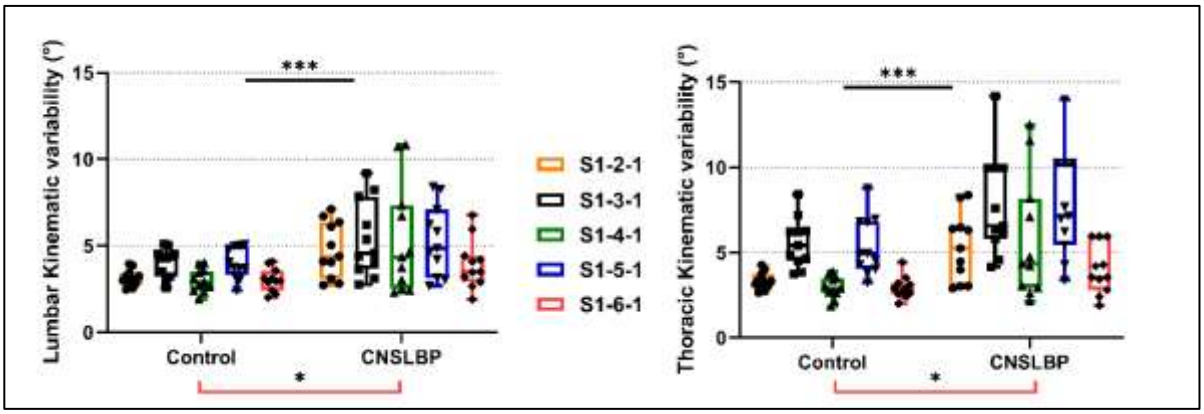


Figure 4.6: **Thoracic and lumbar kinematic variability differences between people with CNSLBP and healthy controls in the Frontal plane of motion**

Box plot displays the range from minimum to maximum values, with individual data points shown; **S1-2-1:** shelf1 to shelf2 to shelf1. The lower line represent the statistically significant main effect of group, the upper line represent the statistically significant main effect of shelf: ***p*<0.05*; **p*< 0.005*; *** p*< 0.001

For the lumbar segment, there was a significant main effect of group; people with CNSLBP presented with greater lumbar kinematic variability (F= 6.11, p=0.022, ηp^2=0.234) compared with healthy controls and again this was independent of the five lifting movements. The lumbar kinematic variability for the CNSLBP group was 4.94°±0.43(SE), whereas for the healthy controls it was 3.44°±0.43(SE) with a mean difference of 1.50° and 95% CI=0.236, 2.776. Further, there was a significant main effect of shelf (F= 8.15, p<0.001, ηp^2=0.290); lumbar kinematic variability was again found to be higher for movements to the lower shelves (S3, S5) (Bonferroni post-hoc results are shown in **Table 4.3**). However, no group by shelf interaction effect was observed for the measure of lumbar kinematic variability (F= 2.24, p=0.106, ηp^2=0.101) (**Figure 4.6**).

Table 4.3: **Results of Bonferroni post hoc multiple comparisons for shelf height effect on the thoracic and lumbar kinematic variability in all planes of motions.**

S2: Shelf2, S3: Shelf3, S4: Shelf4, S5: Shelf5, and S6: Shelf6

****p***<0.05; *****p***< 0.005; *** ***p***< 0.001

SAGITTAL PLANE							
Thoracic Kinematic variability							
Shelf (°)	**Shelf**	**Mean**	**Mean Difference**	**Std. Error**	**Sig. *p* value**	**95% Confidence Interval for Difference**	
						Lower Bound	**Upper Bound**
S2 (4.005)	S3	6.053	-2.049*	.614	.033	-3.984	-.113
	S4	3.864	.141	.224	1.000	-.565	.846
	S5	6.905	-2.900*	.812	.019	-5.459	-.340
	S6	3.639	.365	.299	1.000	-.577	1.308
S3 (6.053)	S2	4.005	2.049*	.614	.033	.113	3.984
	S4	3.864	2.189**	.563	.009	.413	3.966
	S5	6.905	-.851	.381	.371	-2.053	.350
	S6	3.639	2.414**	.619	.009	.461	4.368
S4 (3.864)	S2	4.005	-.141	.224	1.000	-.846	.565
	S3	6.053	-2.189**	.563	.009	-3.966	-.413
	S5	6.905	-3.041**	.751	.006	-5.408	-.674
	S6	3.639	.225	.412	1.000	-1.075	1.525
S5 (6.905)	S2	4.005	2.900*	.812	.019	.340	5.459
	S3	6.053	.851	.381	.371	-.350	2.053
	S4	3.864	3.041**	.751	.006	.674	5.408
	S6	3.639	3.265**	.755	.003	.884	5.647
S6 (3.639)	S2	4.005	-.365	.299	1.000	-1.308	.577
	S3	6.053	-2.414**	.619	.009	-4.368	-.461
	S4	3.864	-.225	.412	1.000	-1.525	1.075
	S5	6.905	-3.265**	.755	.003	-5.647	-.884
Lumbar Kinematic variability							
S2 (3.941)	S3	4.798	-.857*	.245	.022	-1.629	-.085
	S4	4.103	-.162	.165	1.000	-.682	.357
	S5	5.890	-1.950**	.428	.002	-3.298	-.601
	S6	4.077	-.137	.211	1.000	-.803	.529
S3 (4.798)	S2	3.941	.857*	.245	.022	.085	1.629
	S4	4.103	.695**	.204	.028	.051	1.338

	S5	5.890	-1.092	.373	.082	-2.267	.082
	S6	4.077	.720	.332	.424	-.327	1.768
S4 (4.103)	S2	3.941	.162	.165	1.000	-.357	.682
	S3	4.798	-.695*	.204	.028	-1.338	-.051
	S5	5.890	-1.787***	.333	<.001	-2.837	-.738
	S6	4.077	.025	.215	1.000	-.651	.702
S5 (5.890)	S2	3.941	1.950**	.428	.002	.601	3.298
	S3	4.798	1.092	.373	.082	-.082	2.267
	S4	4.103	1.787***	.333	<.001	.738	2.837
	S6	4.077	1.813*	.389	.002	.586	3.039
S6 (4.077)	S2	3.941	.137	.211	1.000	-.529	.803
	S3	4.798	-.720	.332	.424	-1.768	.327
	S4	4.103	-.025	.215	1.000	-.702	.651
	S5	5.890	-1.813**	.389	.002	-3.039	-.586
TRANSVERSAL PLANE							
Thoracic Kinematic variability							
S2 (2.775)	S3	7.202	-4.427***	.785	<.001	-6.903	-1.951
	S4	3.780	-1.005**	.300	.032	-1.951	-.059
	S5	6.236	-3.461***	.642	<.001	-5.486	-1.437
	S6	2.627	.148	.395	1.000	-1.098	1.393
S3 (7.202)	S2	2.775	4.427***	.785	<.001	1.951	6.903
	S4	3.780	3.422***	.662	<.001	1.334	5.510
	S5	6.236	.965	.429	.358	-.387	2.318
	S6	2.627	4.575***	.925	<.001	1.657	7.492
S4 (3.780)	S2	2.775	1.005**	.300	.032	.059	1.951
	S3	7.202	-3.422***	.662	<.001	-5.510	-1.334
	S5	6.236	-2.456**	.602	.006	-4.353	-.559
	S6	2.627	1.153	.400	.092	-.108	2.413
S5 (6.236)	S2	2.775	3.461***	.642	<.001	1.437	5.486
	S3	7.202	-.965	.429	.358	-2.318	.387
	S4	3.780	2.456**	.602	.006	.559	4.353
	S6	2.627	3.609**	.767	.001	1.190	6.028
S6 (2.627)	S2	2.775	-.148	.395	1.000	-1.393	1.098
	S3	7.202	-4.575***	.925	<.001	-7.492	-1.657
	S4	3.780	-1.153	.400	.092	-2.413	.108
	S5	6.236	-3.609**	.767	.001	-6.028	-1.190
Lumbar Kinematic variability							
S2 (2.495)	S3	5.586	-3.091***	.592	<.001	-4.957	-1.225
	S4	4.054	-1.559***	.314	<.001	-2.550	-.568
	S5	4.542	-2.046**	.495	.005	-3.608	-.485

	S6	3.538	-1.043	.366	.099	-2.198	.112
S3 (5.586)	S2	2.495	3.091***	.592	<.001	1.225	4.957
	S4	4.054	1.532	.517	.077	-.097	3.161
	S5	4.542	1.045	.378	.119	-.147	2.236
	S6	3.538	2.048**	.490	.005	.503	3.593
S4 (4.054)	S2	2.495	1.559***	.314	<.001	.568	2.550
	S3	5.586	-1.532	.517	.077	-3.161	.097
	S5	4.542	-.487	.343	1.000	-1.568	.594
	S6	3.538	.516	.349	1.000	-.583	1.615
S5 (4.542)	S2	2.495	2.046**	.495	.005	.485	3.608
	S3	5.586	-1.045	.378	.119	-2.236	.147
	S4	4.054	.487	.343	1.000	-.594	1.568
	S6	3.538	1.003*	.288	.023	.097	1.910
S6 (3.538)	S2	2.495	1.043	.366	.099	-.112	2.198
	S3	5.586	-2.048**	.490	.005	-3.593	-.503
	S4	4.054	-.516	.349	1.000	-1.615	.583
	S5	4.542	-1.003*	.288	.023	-1.910	-.097
FRONTAL PLANE							
Thoracic Kinematic variability							
S2 (4.320)	S3	7.773	-3.453***	.683	<.001	-5.606	-1.301
	S4	4.353	-.033	.334	1.000	-1.086	1.019
	S5	7.820	-3.500**	.771	.002	-5.931	-1.069
	S6	3.474	.846**	.215	.008	.167	1.524
S3 (7.773)	S2	4.320	3.453***	.683	<.001	1.301	5.606
	S4	4.353	3.420***	.559	<.001	1.658	5.181
	S5	7.820	-.047	.362	1.000	-1.189	1.095
	S6	3.474	4.299***	.731	<.001	1.995	6.603
S4 (4.353)	S2	4.320	.033	.334	1.000	-1.019	1.086
	S3	7.773	-3.420***	.559	<.001	-5.181	-1.658
	S5	7.820	-3.467***	.657	<.001	-5.538	-1.396
	S6	3.474	.879	.445	.621	-.524	2.282
S5 (7.820)	S2	4.320	3.500**	.771	.002	1.069	5.931
	S3	7.773	.047	.362	1.000	-1.095	1.189
	S4	4.353	3.467***	.657	<.001	1.396	5.538
	S6	3.474	4.346***	.852	<.001	1.659	7.033
S6 (3.474)	S2	4.320	-.846*	.215	.008	-1.524	-.167
	S3	7.773	-4.299***	.731	<.001	-6.603	-1.995
	S4	4.353	-.879	.445	.621	-2.282	.524
	S5	7.820	-4.346***	.852	<.001	-7.033	-1.659
Lumbar Kinematic variability							

S2 (3.953)	S3	4.720	-.767**	.195	.008	-1.380	-.153
	S4	4.157	-.204	.319	1.000	-1.209	.801
	S5	4.660	-.707*	.220	.043	-1.399	-.014
	S6	3.478	.474	.200	.275	-.155	1.104
S3 (4.720)	S2	3.953	.767**	.195	.008	.153	1.380
	S4	4.157	.563	.254	.385	-.238	1.364
	S5	4.660	.060	.130	1.000	-.351	.471
	S6	3.478	1.241***	.249	<.001	.456	2.027
S4 (4.157)	S2	3.953	.204	.319	1.000	-.801	1.209
	S3	4.720	-.563	.254	.385	-1.364	.238
	S5	4.660	-.503	.287	.954	-1.409	.403
	S6	3.478	.678	.371	.822	-.491	1.847
S5 (4.660)	S2	3.953	.707*	.220	.043	.014	1.399
	S3	4.720	-.060	.130	1.000	-.471	.351
	S4	4.157	.503	.287	.954	-.403	1.409
	S6	3.478	1.181**	.248	.001	.399	1.963
S6 (3.478)	S2	3.953	-.474	.200	.275	-1.104	.155
	S3	4.720	-1.241***	.249	<.001	-2.027	-.456
	S4	4.157	-.678	.371	.822	-1.847	.491
	S5	4.660	-1.181**	.248	.001	-1.963	-.399

4.5 Discussion

This study investigated the kinematic variability of spinal movement during repetitive lifting to test whether people with CNSLBP present with differences in trunk angular displacement variability as a potential motor adaptation to chronic pain. The results of this study showed no differences in thoracic nor lumbar ROM between asymptomatic individuals and people with CNSLBP when executing the repetitive loaded lifting task between six shelves arranged in a multi-planar manner. However, people with CNSLBP performed the task with significantly higher thoracic and lumbar kinematic variability between the ten cycles of lifting movements. This effect was observed in all five lifting movements in the sagittal, transverse and frontal planes of motion.

Recently, cross-sectional evidence demonstrated that people with LBP tend to lift with a slower, deeper squat with less spinal ROM compared to asymptomatic people (Nolan et al., 2020, Saraceni et al., 2021). However, in the current study a similar ROM was observed for both groups, and this was expected given the standardisation of the lifting task. The heights of the shelves which determined the ROM were individualised for each participant; therefore, no differences were expected or observed while executing the lifting movements (Matheve et al., 2019).

Interestingly, those with CNSLBP, despite performing the task with the same ROM as asymptomatic individuals, showed a different strategy to execute the lifting task with higher cycle-to-cycle variation. Previous studies which have examined spinal kinematics during a repetitive lifting task have revealed that people with chronic LBP present with different movement control strategies when compared with asymptomatic individuals (Asgari et al., 2017, Bauer et al., 2015, Dideriksen et al., 2014, Fujii et al., 2022, Moreno Catalá et al., 2018, Pranata et al., 2018). A more common observation in kinematic variability is an increase in kinematic variation in the sagittal plane of motion when picking up a box from the floor (Bauer et al., 2015). The same finding was observed in the current study albeit while performing a more complex multi-planar lifting task.

There are several possible explanations for the increased spinal kinematic variability observed for those with CNSLBP, for example, it may reflect an attempt to avoid aggravating pain or an attempt to minimise back muscle fatigue. The relationship between motor variability and fatigue has been explored previously based on the variability in muscle activation (Falla et al., 2014, Farina et al., 2008), which revealed that higher variability can lead to longer endurance and reduced development of fatigue in healthy volunteers (Farina et al., 2008). In contrast, people with LBP have reduced variability of back muscle activity during repetitive lifting tasks and this is thought to contribute to pain provocation during task performance (Falla et al., 2014). In the current study

however, people with CNSLBP presented with greater perceived exertion despite higher kinematic variability.

Although the increased variability may indicate adaptive responses aimed at minimising pain or fatigue, it is crucial to understand the nature of this variability. Without further analysis, determining whether it corresponds to high variability that is predictable or high variability that is random remains uncertain. Identifying where this variability lies on the Stergiou map is crucial, as predictable variability may influence task adaptation, while random variability could introduce challenges for motor control. Therefore, understanding the structure of variability is essential for comprehending its implications for motor control strategies and its potential impact on pain perception and task performance in individuals with CNSLBP.

While pain and fatigue are considered potential explanations for the higher kinematic variability in CNSLBP people, other research proposes that differences in spinal kinematics compared to asymptomatic individuals may be influenced by psychological pain-related factors, such as fear of movement (Fujii et al., 2022, Fujii et al., 2021). Although those with CNSLBP that were recruited in the current study presented with higher levels of fear of movement compared with asymptomatic individuals, the limited number of participants in our study prevented us from examining any potential associations between clinical and kinematic variables.

4.5.1 Methodological considerations

Certain limitations of this study need to be acknowledged. Firstly, we included a relatively small sample size and this prevented us from investigating any potential correlations between kinematic variability and pain-related factors. Nevertheless, we were still able to determine significant differences in spinal kinematic variability between groups. Despite the modest mean differences in kinematic variability of around three degrees, the effect sizes ranged from moderate to large.

Nevertheless, it remains unclear whether this is a clinically meaningful difference. However, this study provides new insights into motor adaptations to CNSLBP, which may lead to targeted interventions that can potentially improve the management of individuals with CNSLBP.

4.6 Conclusion

People with CNSLBP completed a standardised repetitive lifting task with the same spinal ROM as asymptomatic individuals, yet, with a different motor control strategy to execute the lifting task which was characterised by higher kinematic cycle-to-cycle variation.

CHAPTER 5

ESTIMATING TRUNK KINEMATIC VARIABILITY VIA DISPERSION OF THE FINITE HELICAL AXES

This chapter presents the full contents of a manuscript that has been prepared for publication along changes made in the text specifically for the context of this thesis.

Presentations:

1. **Amal M. Alsubaie**, Corrado Cescon, Eduardo Martinez-Valdes, Marco Barbero, and Deborah Falla. Methodological analysis of finite helical axis behaviour to assess trunk motor variability during repetitive movements. International Society of Electrophysiology and Kinesiology (ISEK). Québec City, Canada, June 22 - 25, 2022.
2. **Amal M. Alsubaie**, Corrado Cescon, Eduardo Martinez-Valdes, Marco Barbero, and Deborah Falla**.** Methodological analysis of finite helical axis behaviour to assess trunk motor variability during repetitive movements. The 13th Australasian Biomechanics Conference (ABC13). Brisbane, QLD, Australia, November 27 -29, 2022.
3. **Amal M. Alsubaie,** Corrado Cescon, Eduardo Martinez-Valdes, Marco Barbero, and Deborah Falla. Estimating trunk kinematic variability via dispersion of the finite helical axes. The Chartered Society of Physiotherapy (CSP) Annual Conference 2023. Birmingham, United Kingdom, November 1, 2023.

5.1 Abstract

Spine kinematics have been investigated using a wide range of analytical methods that characterise movement. The HA of motion is one of the recently proposed approaches to functionally investigate 3D joint kinematics since the HA allows the evaluation of kinematic variability. The aim of this study was to describe the dispersion of HA parameters between three spinal segments (i.e., thoracic, lumbar, and sacral) during repetitive uniplanar trunk movements in response to changes in plane and speed of motion in healthy volunteers. Differences in trunk muscle co-activation between conditions was also examined. Twenty asymptomatic individuals performed repetitive cyclic trunk movements (i.e., flexion-extension, rotation and side bending) while spinal kinematics and electromyography were captured. Higher dispersion of the helical axes was observed during trunk side bending movements (thoraco-lumbar: $F=26.72$, $p<0.001$, $\eta p^2=0.585$; lumbo-sacral: $F=128.6$, $p<0.001$, $\eta p^2=0.871$), especially at slower speeds (thoraco-lumbar: $F=7.57$, $p<0.01$, $\eta p^2=0.285$). Rotational movements were characterised by a higher level of trunk muscle co-activation ($F=24.21$, $p<0.001$, $\eta p^2=0.560$) accompanied by lower kinematic variability and higher stability. The use of the HA measures to describe trunk kinematic variability may offer new insight into trunk motor control strategies and how they are adapted, for example, in people with low back pain.

5.2 Introduction

As outlined in *Chapter One*, spine kinematics have been investigated using wide range of analytical methods that characterise kinematics in terms of vertebral translation and rotation, where the majority of rotational angles have been analysed in in-vitro studies (Schmidt et al., 2008). Both relative rotation and translation of the vertebrae in all three anatomical planes are fundamental aspects for normal physiological spinal motion (Metzger et al., 2010). ROM with Euler angles or other angular representations are most commonly used to examine joint kinematics, yet other techniques, such as the FHA, may allow to detect pathological 3D spine motion more effectively (Ancillao, 2022, McLachlin et al., 2016). FHA methods provide more detailed, less constrained (6-DOFs), and time–dependent representations of joint kinematics, when compared with other approaches for the estimation of functional joint axes (i.e., symmetrical axis of rotation approach (SARA), instantaneous helical axis (IHA)) (Ancillao, 2022, De Benedictis, 2022). In addition, the analysis of the HA defines the movement of two segments by reducing them into a rotation about and translation along a single axis, which allows the evaluation of joint movement variability in repetitive motion (Alsultan et al., 2019, Cripton et al., 2001, Grip and Häger, 2013, Grip et al., 2015).

Recently, the behaviour of HA has been studied in vivo on several joints such as the knee joint (Grip and Häger, 2013, Grip et al., 2015, Grip et al., 2019, Konda et al., 2019, Markström et al., 2020, Temporiti et al., 2020), shoulder joint (Temporiti et al., 2019), temporomandibular joint (TMJ) (Gallo et al., 1997, Gallo et al., 2006), and metacarpophalangeal (MCP) joint (Fioretti et al., 1990). The HA has also been studied in vitro on cadaveric elbows (Muriuki et al., 2012). However, the behaviour of HA in vivo during spinal movements has only been applied to investigate cervical spine movement (Alsultan et al., 2019, Barbero et al., 2017, Cattrysse et al., 2020, Cescon et al., 2014, Dugailly et al., 2015, Ellingson et al., 2013, Grip et al., 2008, Woltring et al., 1994). In

contrast, the lumbar spine has mainly been investigated using HA methods either in vitro or in simulation studies (Ellingson and Nuckley, 2015, Metzger et al., 2010, Rockenfeller et al., 2021, Schmidt et al., 2008, Wachowski et al., 2009). To date there have been no attempts to describe the behaviour of the HA during trunk motion without the need for a 3D reconstruction of the bones of the joint.

The findings regarding kinematic variability in individuals with CNSLBP, as discussed in *Chapter Three* and *Chapter Four*, relied on linear measures of variability (i.e., Mean SDs). Therefore, the objective of the current chapter was to examine HA parameters between three spinal segments (thoracic, lumbar, and sacral) in order to reveal more information about movement variability through capturing the complex 3D nature of spinal motion in a way that linear measures of variability alone might not capture. In the current chapter, asymptomatic volunteers engage in repetitive uniplanar movements, varying both the plane and speed of motion. This approach aims to introduce a novel method for assessing kinematic variability in trunk motion. Based on results from previous studies focused on the cervical spine, we hypothesised that HA parameters will provide a new analytical tool capable of detecting differences in kinematic variability with changing plane and speed of motion (Alsultan et al., 2019, Alsultan et al., 2020, Barbero et al., 2017); and might be used in future for testing kinematic variability during repetitive trunk motion with the presence of spine pathologies. Furthermore, considering recent motor control theories that propose an association between trunk movement variability and muscle activity, an additional objective was to assess the level of trunk muscle co-activation during these movements and how these relate to the degree of kinematic variability (van Dieën et al., 2019b).

5.3 Methods

5.3.1 Design and setting

This observational cross-sectional study was conducted at the Centre of Precision Rehabilitation for Spinal Pain (CPR Spine), University of Birmingham, UK. Ethical approval for the study was granted by the Ethics Committee of the University of Birmingham (ERN_19-1862: **Appendix 8**) and the study was conducted according to the Declaration of Helsinki. All participants provided written informed consent and attended one laboratory session. The study is reported in line with STROBE guidelines (von Elm et al., 2008).

5.3.2 Participants

Twenty healthy volunteers (ten men, ten women) were recruited from students and staff of the University of Birmingham via posters around the University campus and posts on social media. Since no previous study had evaluated parameters of the HA between thoraco-lumbar and lumbo-sacral regions of the spine, no data were available for sample size calculation. Thus, sample size was estimated based on a previous study evaluating parameters of the HA, during movements of the cervical spine (Alsultan et al., 2019). The sample size was calculated using G*Power 3.1.9.4 based on α of 0.05, a power of 0.80, a moderate effect size of (f) 0.23. Considering one group being measured across nine observations, 17 participants were needed to detect a significant effect.

Inclusion and exclusion criteria

We recruited men and women aged between 18 and 55 years. The upper age limit was set at 55 years due to the higher prevalence of age-related changes in the musculoskeletal system with increasing age (Petry, 2002). In addition, the participants were required to 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 care professional. The exclusion criteria were any concurrent systemic issues including rheumatic and neuromuscular disorders which may confound testing, history of chronic respiratory problems, spinal deformity or surgery, cardiovascular conditions and pregnancy.

5.3.3 Questionnaires

Anthropometric data (i.e., age, height, weight) were collected at the beginning of the session. In addition, recent physical activity levels of all participants were assessed by IPAQ questionnaire, which has high content validity in addition to high reliability and inter-method agreement (Booth, 2000, Craig et al., 2003).

5.3.4 3D Kinematics of the trunk

3D movements of the trunk were captured using eight infrared cameras (BTS Bioengineering, Milan, Italy) with a resolution of 2,2 Mpixels (2048×1088 pxs). The kinematic data was acquired at a frequency of 250Hz following system calibration. A modified version of a previously described kinematic trunk model (Preuss and Popovic, 2010) was used. Markers' placement defined three spinal segments using fourteen reflective markers (14mm) placed with double-sided tape over the anatomical landmarks illustrated in **Figure 5.1**. A laser pointer was also fixed using a chest strap over the participant's sternum (5cm below sternal notch).

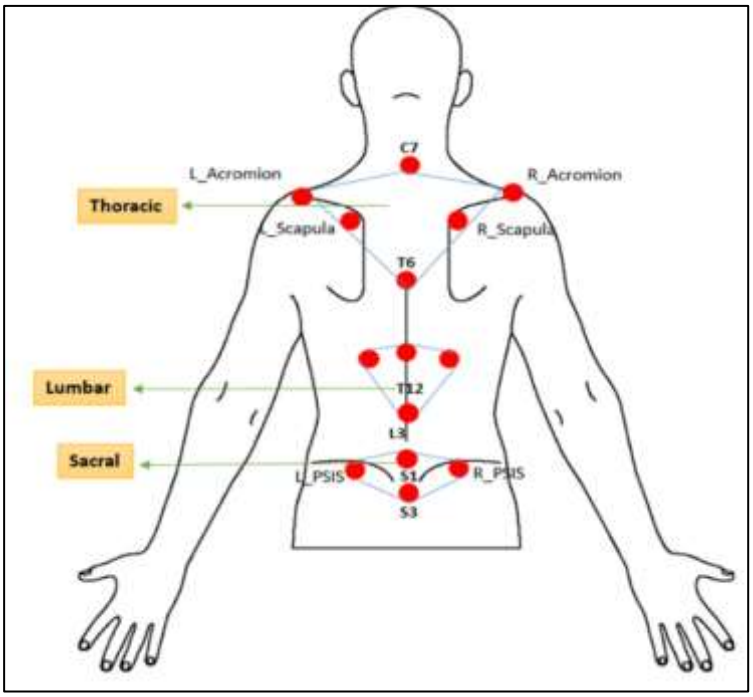


***Figure 5.1*: Markers' placement and spine segmentation for the kinematic model of the spine**

Thoracic segment: spinous processes of 7th cervical vertebra (C7), right & left acromion (R & L Ac), right & left scapular spine (R & L Sc), 6th thoracic vertebra (T6). Lumbar segment: 12th thoracic vertebra (T12), at least 50 mm lateral to the spinous process of T12 (R & L T12), 3rd lumbar vertebra (L3). Sacral segment: 1st sacral vertebra (S1), 3rd sacral vertebra (S3), and posterior superior iliac spine (R & L PSIS).

5.3.5 Surface Electromyography (EMG)

Surface EMG was acquired synchronously with the kinematic data. Wireless Bipolar surface electrodes (41,5×24,8x14mm) (FREEEMG, BTS Bioengineering, Milan, Italy, 16-bit resolution, 1000Hz sampling frequency, Common-mode rejection ratio: >110db@50-60Hz) with Ambu WhiteSensor Ag/Ag–Cl disks (size: 36mm×40mm) were placed on the centre of the muscle belly with 20mm inter-electrode distance following the SENIAM recommendations (Hermens et al., 2000).

Twelve pairs of electrodes were positioned and then secured with double sided tape over six trunk muscles bilaterally as follows: Thoracic Erector Spinae (TES) at the level of T9, Lumbar

Erector Spinae (LES) at the level of L3, Latissimus Dorsi (LD), Rectus Abdominus (RA), Obliquus Externus Abdominis (EO) and Obliquus Internus Abdominis (IO). An additional sensor was placed to measure electrocardiogram (ECG) signals for the purpose of filtering the noise that may contaminate trunk muscle EMG.

Prior to the application of electrodes, skin preparation procedures were performed by shaving the area if needed and then applying an abrasive paste (SPES Medica, Genoa, Italy), and finally cleaning the region with water.

5.3.6 Experimental procedure

Following the completion of questionnaires and placement of the electrodes and markers, participants were asked to sit comfortably on a stool with their feet rested on a wooden step and their hips and knees at 90º flexion. They were asked to remain still while a static trial was recorded. From seated position, the participants were asked to perform 30 cycles of repeated trunk flexion/extension, right/left rotation, and right/left side bending at three different speeds (i.e., fast, slow, self-selected speed) in a random order **(Figure 5.2).** The participants were positioned 80 cm in front of a white board and were instructed to cross their arms over their chest while performing the tasks except for the side bending movements, when they were asked to keep their arms by their side.

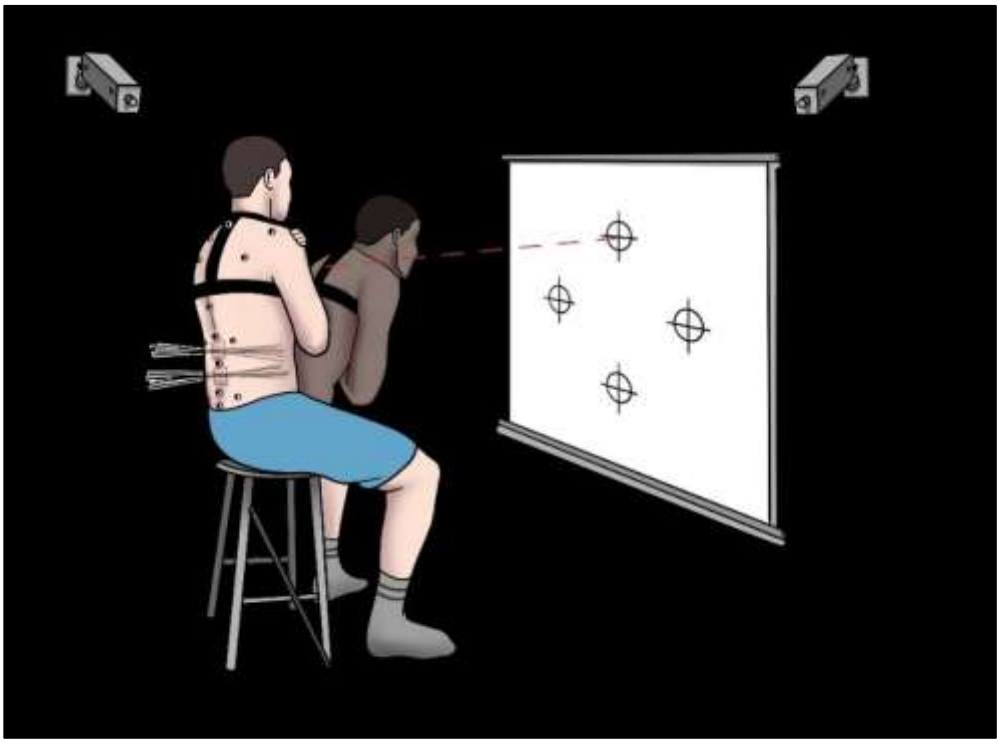


Figure 5.2: **Experimental set-up**

In order to standardise the trunk ROM between participants, they were instructed to use the beam of the laser as a guide to limit their trunk movements by moving between targets: flexion (35º) and extension (15º) movements, and right and left rotational movements (30º each), and right and left side bending (15º each), they were instructed to use their hands to touch a wooden stick placed underneath the stool as a lower right/left target on each side. In order to set up and mark these targets on the board, trunk flexion/extension ROM was measured in degrees with a mobile phone application (iHandy® Level) which was placed at the level of the 12th thoracic vertebra. This phone application has sufficient measurement properties to measure lumbar spine movement (Keogh et al., 2019, Pourahmadi et al., 2020). While for the rotation and side bending ROM, a goniometer was used while subjects were seated before capturing the static trial. The ROM was limited to represent a more functional range that would be encountered during activities of daily living (Bible et al., 2010).

The speed of the movement for the slow and fast speed was controlled using a metronome (Phone mobile application: Metronome®) to establish the movement pace, which was set at 30 and 50 beats per minute for the slow and fast speed respectively. To ensure a smooth completion of movement cycles, the participant was asked to point at a target with each beat (total of 60 beats for 30 cycles). To ensure 30 movement cycles per trial, the slow-paced trials were 120 seconds in duration, while the fast-paced trials were 72 seconds in duration. And to start every trial from a neutral sitting position and then perform continuous trunk movements without stopping in the midline.

Although all movement cycles were recorded, only the middle 15 cycles were analysed to ensure a steady-state movement behaviour (Granata and England, 2006). Every test condition was repeated three times with 90 seconds of rest between trials to minimise fatigue (Agostinete et al., 2016). Three cycles were practised first as familiarisation before the actual recording of each test condition.

5.3.7 Data processing

Data were processed using Matlab (R2022a, MathWorks, MA, USA). The 3D kinematic and EMG data during the repetitive trunk movements tasks were time-normalised using a linear interpolation procedure to obtain 101 samples per cycle (0-100%).

3D Kinematic data

Using BTS SMART software suite (BTS Bioengineering, Italy), data from the markers were tracked and labelled using a custom trunk model and any tracking errors were detected and corrected by eliminating any reflections and maintaining the actual markers. Then, using SMART

Analyzer, 3D markers data were exported in millimetres as a multi-text format files (emt.) for further analysis. Using Matlab (R2022a, MathWorks, MA, USA), a mathematical model was used to evaluate two parameters proposed to describe the behaviour of finite helical axes during joint kinematics: mean angle (MA) and mean distance (MD). These two variables were measured at two spinal levels: between the thoracic and lumbar segments (thoraco-lumbar), and between the lumbar and sacral segments (lumbo-sacral). The selection of thoraco-lumbar and lumbo-sacral regions was made with careful consideration as observing movement between adjacent spinal segments will enhance accuracy in the evaluation of HA dynamics. Given the spine's complex musculature and multi-joint nature, a detailed analysis should consider the relative motion between adjacent segments. The ROM for spinal movements was determined by calculating the degree differences between the maximal flexion and maximal extension of the trunk or between maximum left and right rotation or lateral bending. The group of markers on each spinal segment was identified and analysed as a rigid body, with the adjacent segment serving as the reference frame.

The neutral position of each segment and the end positions (i.e., flexion, extension, rotation, side bending) were identified to create multiple HAs between the two segments **(Figures 5.2 and 5.3).** Once the group of HAs was computed from the movements' cycles, a series of sagittal planes were defined for each spinal level. Handling spinal segments as rigid bodies during the analysis process facilitated determining their orientation, thus helped in establishing the position of the created planes. For the MD computation, the coordinates of intersection points between the group of helical axes and each defined plane were calculated. Subsequently, the barycentre of these intersection points was determined as the average of their coordinates. The distances from each point to the barycentre were then computed and their distribution analysed, taking into account the variability along both the Y and Z axes of the plane (Cescon et al., 2019).

For the MA computation, the unit vector of each HA was extracted, and the mean unit vector was computed. Subsequently, the mean angle of the HAs relative to the mean unit vector was determined. This was achieved by computing the sum of the angles between each HA unit vector and the mean unit vector, divided by the total number of observations or movement cycles (Cescon et al., 2019). Small values of MD and MA indicate that the movement is less variable or more stable (Alsultan et al., 2019, Barbero et al., 2017, Cescon et al., 2014).

MD provides insights into the variability of movement by assessing how spread out the intersection points are along defined planes, with smaller MD values indicating closer proximity between points, signifying less variability and greater consistency in movement. In the context of joint motion, smaller MD values imply greater stability, as the joint is operating in a more controlled manner, resembling an ideal hinge-like motion (Barbero et al., 2017). On the other hand, MA evaluates how individual axes deviate from their mean axis, reflecting the degree of planarity in movement. Lower MA values signify a more planar movement pattern (Barbero et al., 2017). Planar movements are typically more controlled and predictable, exhibiting reduced variability. Therefore, lower MA values not only suggest greater stability due to the constrained nature of planar motion but also indicate reduced variability in movement patterns, contributing to enhanced stability.

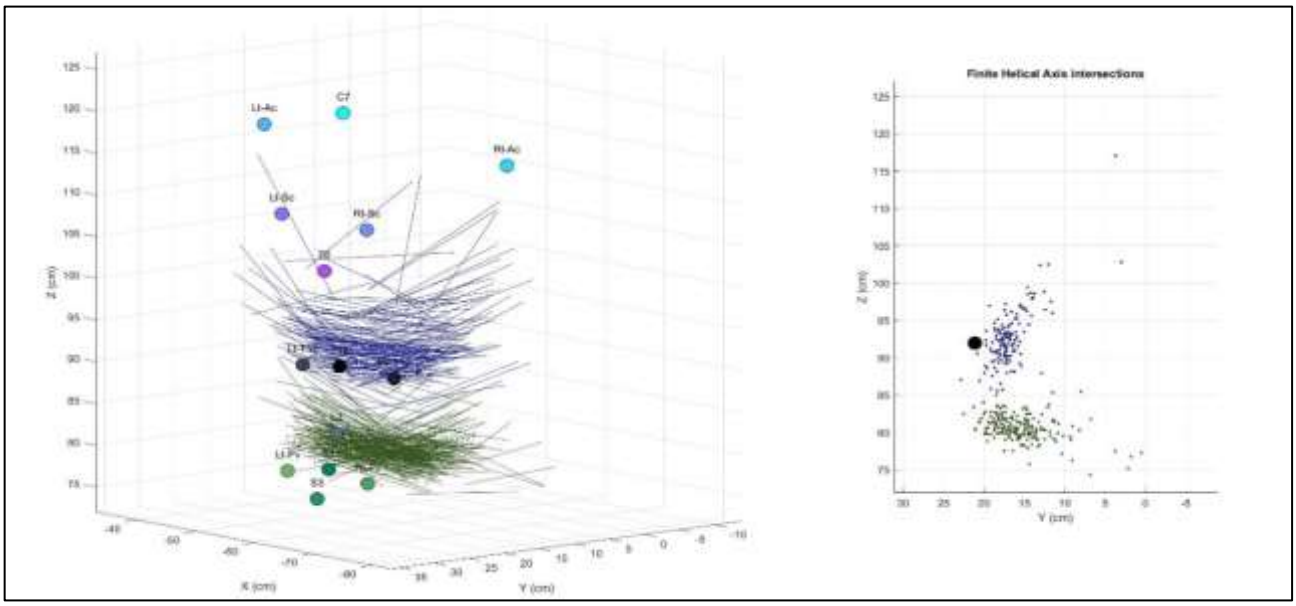


Figure 5.3: **Example of Helical Axis distribution.**

On the left: 3D representation of the HA during 15 flexion/extension cycles. On the right: intersection points with the sagittal plane. Different colours represent the two corresponding spinal segments (Blue: thoraco-lumbar, and Green: lumbo-sacral).

EMG data

sEMG signals were band-pass filtered with cut-off frequencies between 20Hz and 400Hz (2nd order Butterworth filter). The signals were down sampled to 250Hz instead of 1000Hz to match the kinematic data. These signals were then full-wave rectified and filtered again with a low-pass filter (4th order Butterworth filter) with a cut-off frequency of 5Hz. Amplitude-normalisation for the EMG data was conducted using the rectified envelope signal with reference to the peak values of first cycle within the middle 15 analysed cycles (Marras and Davis, 2001).

In order to quantify the degree of muscle co-activation between the trunk muscles, the average EMG amplitude ratio was determined between the agonist and antagonist groups according to the direction of movement (Mueller et al., 2020, Song and Chung, 2004). Which then considered as inputs to measure the time-varying multi-muscle co-activation function (TMCf) to estimate the co-

activation of the six trunk muscles during the task according to the following formula (Ranavolo et al., 2015, Varrecchia et al., 2022):

$$TMCf(d(k),k) = (1 - \frac{1}{1+e^{-12(d(k)-0.5)}}) \times \frac{(\sum_{m}^{M}=1 sEMG_m\ (k)/M)^2}{max_m\ =1 \ldots M\ [sEMG_m\ (k)]}$$

Where

d(k) is the mean of the differences between the *k*th samples of each pair of sEMG signals:

$$d(k) = \frac{\sum_{m-1}^{M-1}\sum_{n=m+1}^{M}|sEMG(k) - sEMG_n\ (k)|}{J(M!/(2\,!\,(M-2)!))}$$

J is the length of the signal;

M is the number of considered muscles;

sEMGm(k) and *sEMGn(k)* are the *k*th sample value of the envelope of the sEMG signals of the m^{th} and n^{th} muscles, respectively.

As a co-activation index, the mean value (TMCf Mean) within the cycles was computed and expressed as a ratio. A higher TMCf Mean value indicates greater simultaneous activation or co-activation of the muscles, whereas a lower TMCf Mean value suggests less co-activation.

5.3.8 Statistical analysis

Normal distribution of the data was confirmed using a Shapiro–Wilk test and thus parametric tests were applied. Descriptive statistics were used to describe the anthropometrics data and questionnaire scores expressed as mean and standard deviation (SD). A Two-way repeated measure Analysis of Variance (ANOVA) was conducted to detect any significant differences of the finite

HA parameters for each spinal level (thoraco-lumbar, lumbo-sacral) between the various test conditions with the three planes and speeds of motion as within subject factors. Significant differences revealed by ANOVA were followed up by post-hoc using Bonferroni corrected t-tests to allow pairwise comparisons. The level of co-activation between the muscles was also evaluated with the same analysis. Effect size has been reported where appropriate with ANOVA results, in the format of ηp^2 values. Effect sizes were interpreted as small when ($\eta p^2 = 0.01$), medium ($\eta p^2 = 0.06$) or large ($\eta p^2 = 0.14$) (Lakens, 2013). Pearson correlation was used to evaluate any associations between the variables. Statistical analysis was performed using SPSS 29 (IBM, USA) with an alpha level set at $\alpha = 0.05$. For all variables, an average was computed across the three trials.

5.4 Results

All 20 participants completed all test conditions. **Table 5.1** presents the participants' characteristics. The majority of the participants had high levels of physical activity according to their score on the IPAQ questionnaire while 30% scored moderate to low levels of activity.

***Table 5.1*: Participants' characteristics and self-reported questionnaires**

****p***<0.05; *****p***< 0.005; *** ***p***< 0.001

	Mean	**Standard deviation**	***p*-value**
Gender (%Males)	50%	-	-
Age (years)	♂ 27.92	4.06	0.46
	♀ 26.39	4.96	
Weight (kg)	♂ 78.54	12.9	0.04*
	♀ 64.09	15.9	
Height (m)	♂ 1.77	0.06	< 0.001***
	♀ 1.64	0.04	
IPAQ scores: Total Walking MET-min/week	1771	1726.5	-
Total Moderate Activities MET-min/week	797.1	1120.7	-
Total Vigorous activities MET-min/week	1235.3	795.5	-

5.4.1 Range of motion and velocity

ROM of each movement cycle are presented in **Table 5.2**. The velocity of each test condition showed that the participants were executing the self-selected speed tasks faster than the prescribed fast speed task especially during the rotational and side bending movement cycles.

Table 5.2: **Mean+SD of the total angular displacement of the thoracic and lumbar spine as well as velocity in all movement planes and speeds.**

		Fast	Self-selected speed	Slow
Flexion/Extension	**Flexion ROM (°)**	38.76±0.96	38.15±0.77	37.69±.0.79
	Extension ROM (°)	17.11±1.00	16.49±0.82	15.76±0.73
	Velocity (mm/s)	569.4±118.3	502.9±105.2	396.9±88.5
Rotation	**Rt. ROM (°)**	28.22±1.05	28.02±1.07	28.11±0.95
	Lt. ROM (°)	28.37±1.03	28.31±1.02	28.23±0.98
	Velocity (mm/s)	369.69±79.1	378.04±78.09	244.85±54.77
Side bending	**Rt. ROM (°)**	22.27±1.67	22.27±1.55	24.7±1.57
	Lt. ROM (°)	22.30±1.58	22.27±1.51	24.75±1.52
	Velocity (mm/s)	414.8±108.5	420.6±110	295.03±77

5.4.2 Helical axis parameters

Mean angle between thoraco-lumbar segments

The two-way repeated measure ANOVA showed a significant main effect of change in plane and speed of motion (F=26.72, p=0.000, ηp^2=0.585; F=7.57, p=0.005, ηp^2=0.285 respectively) **(Figure 5.4)**. An interaction was observed between movement plane and speed (F= 4.6, p=0.008, ηp^2=0.195), with higher MA observed during the slow speed compared to the self-selected speed (p=0.024, mean dif.(95% CI)=1.089,(0.124;2.054)) and the fast speed (p=0.023, mean dif.(95% CI)=0.959, (0.113;1.805)). This was especially the case during side bending movements compared to the flexion/extension (p<0.001, mean dif.(95% CI)=6.021, (3.611;8.432)) and the rotation movements (p<0.001, mean dif.(95% CI)=3.918, (2.081;5.755)).

Mean distance between thoraco-lumbar segments

In contrast to the thoraco-lumbar MA, MD only changed with change in movement plane (F= 4.1, p= 0.027, ηp^2=0.177), with larger MD during flexion/extension (p=0.057, mean dif.(95% CI)=0.675, (-0.017;1.367)) compared to rotational movements, but not with movement speed (F= 1.2, p= 0.31, ηp^2=0.058) and there was no interaction between movement plane and speed (F= 1.7, p= 0.19, ηp^2=0.081) **(Figure 5.4)**.

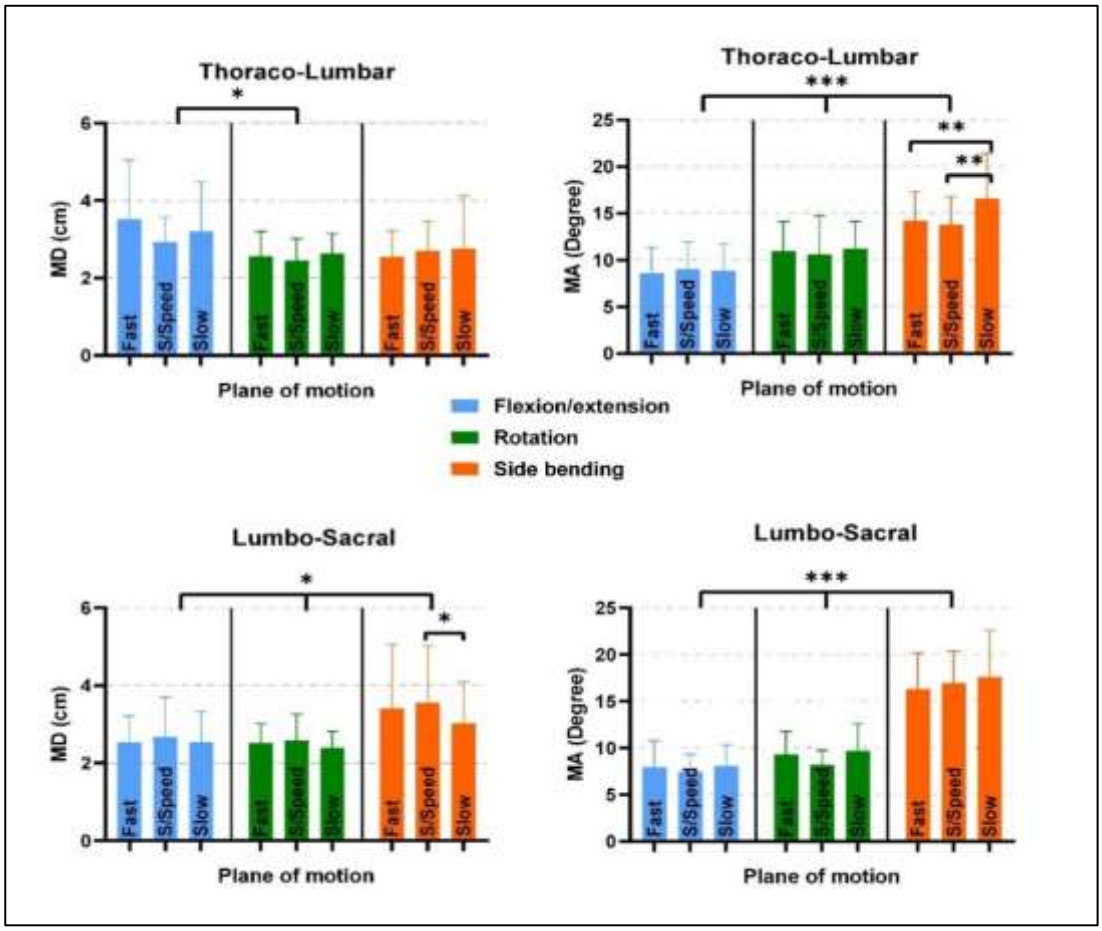


Figure 5.4: **Mean+SD of MD and MA during each movement plane and speed.**

*$p \leq 0.05$;**$p \leq 0.01$; ***$p \leq 0.001$. MD: Mean distance, MA: Mean angle, S/speed: Self-selected speed.

Mean angle between lumbo-sacral segments

The plane of movement significantly influenced the MA (F=128.6, p=0.000, ηp^2=0.871) with higher MA observed during side bending movements compared to flexion/extension (p<0.001, mean dif.(95% CI)=9.094, (7.464;10.724)) and rotation (p<0.001, mean dif.(95% CI)=7.862, (6.043;9.681)). However, there was no effect of speed (F=2.7, p=0.08, ηp^2=0.127) nor an interaction between movement plane and speed (F= 1.15, p= 0.332, ηp^2=0.057) **(Figure 5.4)**.

Mean distance between lumbo-sacral segments

The MD differed significantly with plane and speed of motion (F=5.21, p=0.025, ηp^2=0.215; F=3.32, p=0.047, ηp^2=0.149 respectively). Larger MD was observed during the self-selected speed compared to the slow speed (p=0.045, mean dif.(95% CI)=0.281, (0.005;0.557)), and especially during side bending movements compared to rotation (p=0.041, mean dif.(95% CI)=0.829, (0.028; 1.631)). However, there was no interaction between the two factors (F= 0.85, p=0.47, ηp^2=0.043) **(Figure 5.4)**.

5.4.3 Time-varying multi-muscle co-activation function (TMCf Mean)

There was an effect of plane of motion (F=24.21, p=0.000, ηp^2=0.560) but not speed (F=0.16, p=0.83, ηp^2=0.009) on TMCf mean. Higher co-activation was observed during rotation movements compared to the side bending (p=0.024, mean dif.(95% CI)=0.037, (0.004;0.069)) and flexion/extension movements (p<0.001, mean dif.(95% CI)=0.092, (0.051;0.133)). TMCf mean was also higher during side bending when compared with the flexion/extension movements (p<0.001,

mean dif.(95% CI)=0.055, (0.025; 0.086)). There was also an interaction effect between plane and speed of movement (F=5.69, p=0.001, ηp^2=0.231) (**Figure 5.5)**.

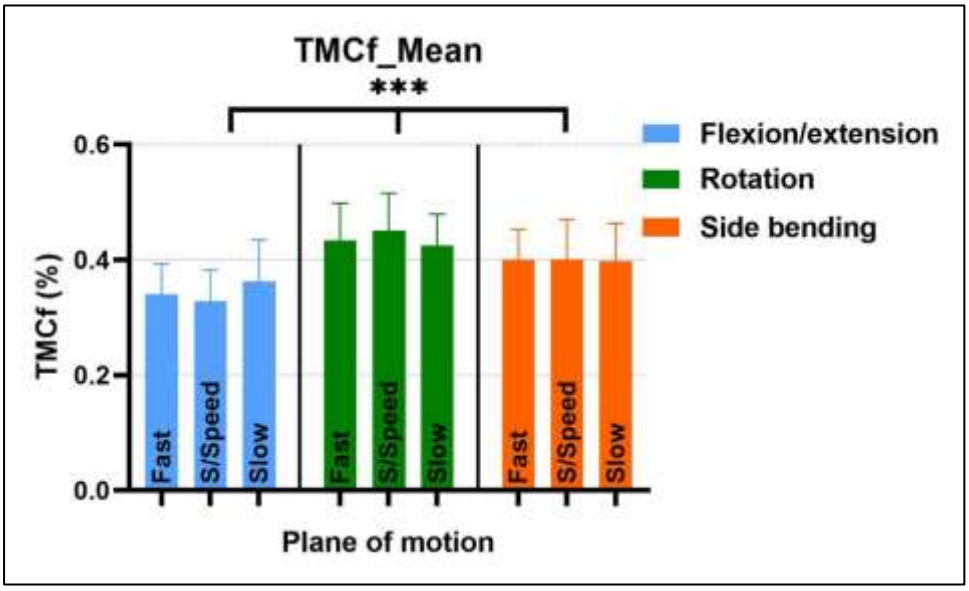


Figure 5.5: Mean+SD of TMCf mean during each movement plane and speed.
p** ≤ 0.05;*p** ≤ 0.01; *****p** ≤ 0.001. MD: Mean distance, MA: Mean angle, S/speed: Self-selected speed.

5.4.4 Correlations between helical axis parameters and other variables

A negative correlation was found between the HA parameters and the co-contraction index (TMCf mean) during some conditions (i.e., flexion/extension at a self-selected speed (p=0.016) and side bending at a slow speed (p<0.05) cycles) **(Figure 5.6 & Table 5.3**), yet a positive correlation (p<0.05) was observed during the rotational cycles regardless of movement speed (**Figure 5.6**). No correlations were observed between HA parameters and movement velocity (p>0.05).

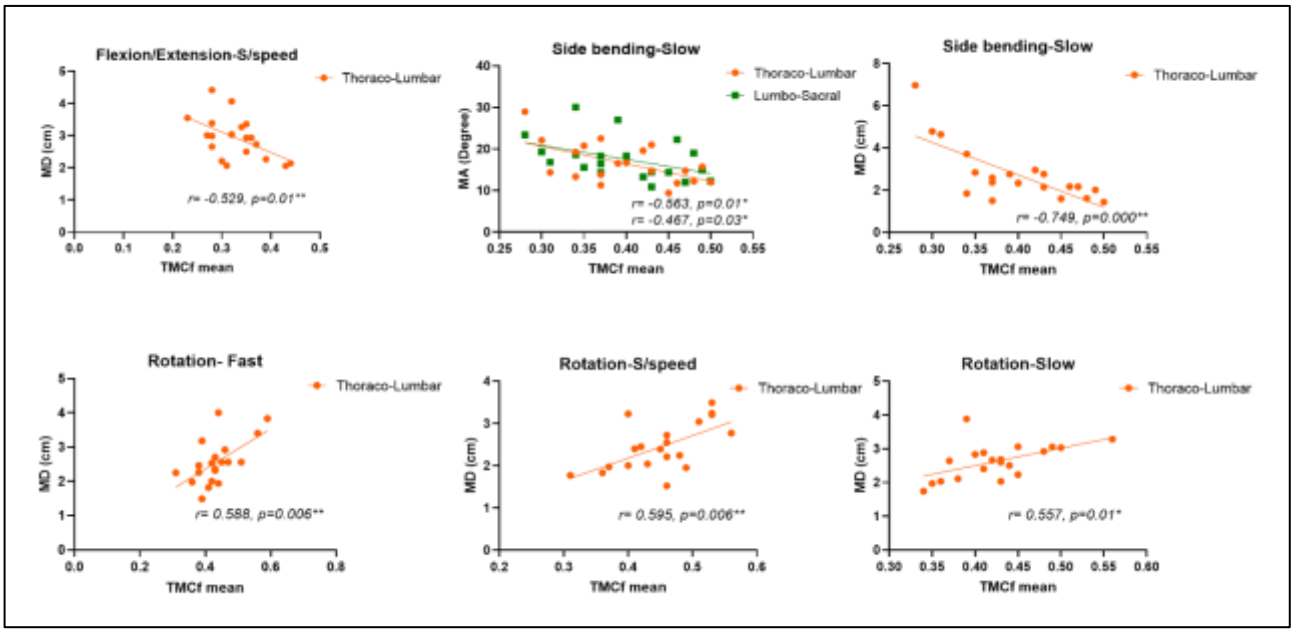


Figure 5.6: **Correlation between MD, MA and time-varying multi-muscle co-activation function (TMCf)**

MD: Mean distance, MA: Mean angle, S/speed: Self-selected speed.

Table 5.3: **Correlations between helical axis parameters (MA&MD) and the co-activation index (TMCf mean)**

MD: Mean distance, MA: Mean angle * ***p***< 0.001

Test Condition	Helical axis parameter	TMCf	Correlation coefficient	Sig. (2-tailed)
Flexion/Extension Fast	MA Thoraco-Lumbar	TMCf mean	-0.257	0.27
	MA Lumbo-Sacral	TMCf mean	0.175	0.46
	MD Thoraco-Lumbar	TMCf mean	-0.262	0.26
	MD Lumbo-Sacral	TMCf mean	-0.146	0.53
Flexion/Extension Self-selected speed	MA Thoraco-Lumbar	TMCf mean	-0.225	0.34
	MA Lumbo-Sacral	TMCf mean	0.165	0.49
	MD Thoraco-Lumbar	TMCf mean	-0.529	0.016
	MD Lumbo-Sacral	TMCf mean	0.094	0.69
Flexion/Extension Slow	MA Thoraco-Lumbar	TMCf mean	-0.312	0.18
	MA Lumbo-Sacral	TMCf mean	0.209	0.38
	MD Thoraco-Lumbar	TMCf mean	-0.437	0.054
	MD Lumbo-Sacral	TMCf mean	0.075	0.75
Rotation Fast	MA Thoraco-Lumbar	TMCf mean	0.124	0.60
	MA Lumbo-Sacral	TMCf mean	0.299	0.20
	MD Thoraco-Lumbar	TMCf mean	0.588	0.006
	MD Lumbo-Sacral	TMCf mean	0.101	0.67

Rotation Self-selected speed	MA Thoraco-Lumbar	TMCf mean	0.059	0.80
	MA Lumbo-Sacral	TMCf mean	0.013	0.96
	MD Thoraco-Lumbar	TMCf mean	0.595	0.006
	MD Lumbo-Sacral	TMCf mean	0.003	0.99
Rotation Slow	MA Thoraco-Lumbar	TMCf mean	-0.012	0.96
	MA Lumbo-Sacral	TMCf mean	0.230	0.33
	MD Thoraco-Lumbar	TMCf mean	0.557	0.01
	MD Lumbo-Sacral	TMCf mean	0.339	0.14
Side bending Fast	MA Thoraco-Lumbar	TMCf mean	-0.372	0.11
	MA Lumbo-Sacral	TMCf mean	-0.035	0.88
	MD Thoraco-Lumbar	TMCf mean	-0.388	0.09
	MD Lumbo-Sacral	TMCf mean	-0.286	0.22
Side bending Self-selected speed	MA Thoraco-Lumbar	TMCf mean	-0.364	0.11
	MA Lumbo-Sacral	TMCf mean	0.147	0.53
	MD Thoraco-Lumbar	TMCf mean	-0.365	0.11
	MD Lumbo-Sacral	TMCf mean	-0.242	0.30
Side bending Slow	MA Thoraco-Lumbar	TMCf mean	-0.563	0.01*
	MA Lumbo-Sacral	TMCf mean	-0.467	0.03*
	MD Thoraco-Lumbar	TMCf mean	-0.749	0.000***
	MD Lumbo-Sacral	TMCf mean	-0.406	0.07

5.5 Discussion

This is the first study to quantify kinematic variability using HA parameters between three spinal segments (thoraco-lumbar, lumbo-sacral). The findings support that HA measure being sensitive to change in movement plane and speed, suggesting increased kinematic variability with slower movement as well as an association between the degree of kinematic variability and trunk muscle co-activation.

5.5.1 Kinematic Variability

Thoraco-lumbar segments - effect of movement speed

The behaviour of HA parameters showed increased kinematic variability with slower speed movements, specifically on MA values with a large effect size, regardless of the plane of

movement. Similar observations have been observed for MA values during cervical spine movement in both asymptomatic individuals and those with chronic neck pain (Alsultan et al., 2019). The same negative correlation between kinematic variability and movement speed during repetitive trunk movements has been reported in a previous study using linear measures to quantify kinematic variability (Asgari et al., 2015). This suggests that incorporating assessments of movement speed and kinematic variability may provide valuable insights into the functional limitations experienced by individuals with spinal pain (Alsultan et al., 2019).

Increased kinematic variability during slower movements could reflect an attempt to accomplish the high demanding task more effectively, given that the participants were performing the task within a predetermined and premeasured ROM. This may be explained by Plamondon and Alimi (1997) kinematic theory suggesting speed-accuracy trade-offs in human movements.

Thoraco-lumbar segments - effect of movement plane

Movement plane had an effect on both MA and MD values with large effect sizes, revealing increased kinematic variability during flexion/extensions movement compared to rotational movement. A previous study investigated the interaction between FHA and facet joint loads on the lumbar spine showed higher joint force production with rotational movement (Schmidt et al. 2008). Collectively, these results suggest high thoraco-lumbar stability (i.e., reduced variability) during rotational movements when compared with other planes of motion. Similarly, performing cervical rotation consistently showed the same orientation and position of the cranio-cervical complex, possibly due to the simplicity of active cervical rotation, which predominantly occurs in the horizontal plane (Barbero et al., 2017). In addition, high kinematic variability based on MA values was observed for the thoraco-lumbar region during side bending movements, which is in line with

previous in-vivo studies examining cervical spine motion (Alsultan et al., 2019, Barbero et al., 2017). The increased dispersion of HA parameters during side bending movement supports the proposed increased spinal instability on this plane of motion (Ellingson and Nuckley, 2015).

Lumbo-sacral segments - Effect of movement speed

In contrast to the observed changes for the thoraco-lumbar region, for the lumbo-sacral region there was no variation in MA values with movement speed, however a significant effect of speed did occur for the measure of MD with large effect size. However, this effect is not consistent with the previous result at the thoraco-lumbar region, as the fastest cycles of motion during the self-selected speed trials showed higher MD values when compared to the slower speed. Although this does not support the speed-accuracy trade-off theory (Plamondon and Alimi, 1997), a previous study that measured both trunk kinematic variability and stability concluded that lower paced movement is associated with greater local stability and motor variability (Asgari et al., 2015). This inconsistency between the results of MA and MD values for the two spinal regions might be attributed to the stability of the movement as MD in particular quantifies the reciprocal distance among helical axes providing a measure of joint rotation centre, whereas MA relates more to the ability to maintain a constant plane of motion (Temporiti et al., 2020, Temporiti et al., 2019). Consequently, MD might be a more sensitive index of joint stability, whereas MA is mainly sensitive to changes in kinematic variability. MD values could provide an index for increased trunk instability because of the higher task demands while performing fast repetitive movements (Wang et al., 2021).

Lumbo-sacral segments - Effect of movement plane

The changes observed for movement plane were consistent with what was observed for the thoraco-lumbar region, however, measures from the lumbo-sacral region revealed an effect on both MA and MD values showing higher kinematic variability during side bending movements regardless of the movement speed. In addition to the previous observations on kinematic variability with different planes of neck movement (Alsultan et al., 2019, Barbero et al., 2017), a recent simulation study examined the FHA behaviour at the lumbar spine within both reduced model and complex model (Rockenfeller et al., 2021). Both models support the current in-vivo results, showing that trunk side bending movements in the frontal plane creates more dispersion or noise in the behaviour of the FHA, especially in the lower lumbar region.

5.5.2 Muscle co-activation

Trunk muscle co-activation was assessed by an algorithm that does not require a-priori classification of the muscles depending on the generated moment and can be used to assess simultaneous co-activation of more than two muscles (Ranavolo et al., 2015). Two recent in-vivo studies investigated the relationship between HA parameters and muscle activity (Adamo et al., 2020, Bishop et al., 2020). Yet, no study has examined the relationship between the degree of muscle co-activation and HA parameters. In line with previous literature (Schinkel-Ivy and Drake, 2019, Silvestri et al., 2013), the highest level of trunk muscle co-activation was observed during rotational movements with a large effect size, while the flexion/extension cycles produced the lowest co-activation regardless of movement speed. The higher level of co-activation observed during rotational movements supports our findings of the reduced helical axes parameters, which means higher co-activation is accompanied with lower kinematic variability and higher stability

(Lee et al., 2006). In the case of trunk rotational movement, the simultaneous activation of both agonists and antagonists were high which imposes a physiological cost that may lead to increased loading on the spine, faster time to fatigue, or neuromuscular inefficiency (Le et al., 2017).

In addition, a negative correlation was found between the co-activation index and HA parameters during side bending movements although this was not the case for all test conditions.

5.5.3 Methodological considerations

Despite the use of a preferable motion capture system that showed less error in the estimation of the FHA compared to other systems (Cescon et al., 2015), this system is prone to skin artefacts that may have not been completely eliminated due to possible shifts of the reflective markers during movements. Furthermore, the ground reaction forces were not assessed, and this may prove useful to correlate kinetics with helical axes parameters. Another aspect to consider is the potential effect of including acromion markers on HA variation, particularly when accounting for the potential relative movement of the acromion markers to the spine due to potential shoulder girdle movement during the task. However, this was mitigated by treating the thoracic spine segment, including the acromion markers, as a rigid body during the analysis. This approach aimed to reduce the potential impact of marker placement variation on HA variability. Finally, pelvic movement was not constrained although any unnecessary pelvic movements was limited by asking the participants to perform the tasks while sitting.

While the EMG signals were normalised using the peak of the initial cycle, this may raise concerns about potential bias in determining the peak level which may introduce between-cycle variation. Therefore, to address this, potentially a more robust normalisation method, involve using

of the mean across the cycle peaks, could provide a more consistent and representative baseline for normalisation.

5.6 Conclusion

Higher dispersion of the HA parameters were observed during trunk side bending movements especially at slower speeds, while the rotational movements were characterised by a higher level of trunk muscle co-activation accompanied with lower kinematic variability and higher stability. Importantly this work shows that HA parameters are sensitive to changes in movement plane and movement speed. The use of the HA measures to describe trunk kinematic variability and stability may offer new insight into trunk motor control strategies and how they are adapted, for example, in people with LBP.

CHAPTER 6

GREATER SPINAL KINEMATIC VARIABILITY IN PEOPLE WITH CHRONIC LOW BACK PAIN REVEALED BY ALTERNATIONS IN HELICAL AXIS PARAMETERS

This chapter reports in full the contents of a manuscript that has been submitted for publication and is currently under review for publication in Journal of Biomechanics. It incorporates the original submission, tailored for this thesis, along with supplementary findings concerning trunk EMG that have not been submitted for publication due to the restrictions in the word limits of the journal.

Presentations:

1. **Amal M. Alsubaie,** Corrado Cescon, Eduardo Martinez-Valdes, Marco Barbero, and Deborah Falla. Spinal kinematic variability is increased in people with chronic low back pain. The Chartered Society of Physiotherapy (CSP) Annual Conference 2023. Birmingham, United Kingdom, November 1, 2023.

6.1 Abstract

Differences in spine kinematics is a common motor adaptation to pain observed in people with LBP compared with asymptomatic individuals and this includes changes in trunk angular displacement, angular velocity, and variability. The HA of motion is an approach to functionally investigate 3D variability of joint kinematics. In this study we investigate whether the variability of trunk movement is modified in people with CNSLBP by measuring the dispersion of HA parameters during repeated trunk movements performed at different speeds. Nineteen people with CNSLBP and twenty asymptomatic volunteers performed repetitive continuous trunk movements at three different speeds. Two parameters of the HA were extracted to characterise movement variability at the thoraco-lumbar and lumbo-sacral regions: mean angle (MA) and mean distance (MD). Two-Way Mixed ANOVA showed significantly higher MA and MD (p<0.001) measured at the thoraco-lumbar region for those with CNSLBP regardless of the plane or speed of movement. Higher HA parameters for those with CNSLBP at the lumbo-sacral region was only observed during flexion/extension cycles of movement. Higher level of back pain intensity was associated with lower values of MA and MD (p<0.05). In addition, higher fear was associated with lower values of MA and MD (p<0.05) specifically for the thoraco-lumbar region during side bending movements. People with CNSLBP people move their spine in a more variable way regardless of the speed or plane of trunk movement. This may reflect an adaptive behaviour to long-lasting pain.

6.2 Introduction

As outlined in *Chapters One* through *Four*, there is a widely acknowledged understanding that individuals experiencing CNSLBP move differently compared to pain free individuals (Hodges and Tucker, 2011, Solomonow, 2011). As an attempt to understand how movement is controlled in the presence of LBP, trunk motor control has been studied extensively by evaluating both trunk muscle activity and trunk movement patterns (van Dieën et al., 2019b). Previous research demonstrated that individuals with chronic LBP often exhibit inconsistent intra-individual movement variability between repetitions when performing repetitive trunk bending. This is evident as either heightened kinematic variability (Bauer et al., 2017) or increased trunk movement stability compared to pain-free individuals (Asgari et al., 2015). Nevertheless, some studies have shown no differences in movement variability between people with and without chronic LBP (Graham et al., 2014, Mokhtarinia et al., 2016). In light of a recent review and supported by our findings outlined in *Chapter Two*, this discrepancy is due to the varying methodologies and metrics used to assess and interpret movement variability (Alsubaie et al., 2023a, Dijk et al., 2021).

The recently proposed parameters of HA (i.e., MA and MD), as introduced in *Chapter Five* for investigating kinematic variability, have demonstrated an excellent reliability during active cervical motion (Barbero et al., 2017). Lower values of MD and MA indicate reduced variability when performing repetitive movements (Alsultan et al., 2019). HA parameters have also been used in research as an index of joint stability, which means a higher stability index is indicative of lower variable movement (Cescon et al., 2019).

Investigating the cervical spine using parameters of HA in those with chronic neck pain compared to asymptomatic participants, revealed less variable movement i.e., decreased MA and MD for those with chronic neck pain (Alsultan et al., 2019). In addition, HA parameters also detected reduced movement variability as a result of acute neck muscle soreness (Alsultan et al.,

2020). To date, only the cervical spine has been assessed using parameters of the HA to determine spinal kinematic variability. In contrast, the lumbar spine has mainly been investigated using HA methods either in vitro or in simulation studies (Ellingson and Nuckley, 2015, Metzger et al., 2010, Rockenfeller et al., 2021, Schmidt et al., 2008, Wachowski et al., 2009).

Therefore, the aim of this study was to examine trunk kinematic variability via parameters of the HA in people with CNSLBP compared to asymptomatic individuals who were tested in *Chapter five*, during three uniplanar repetitive seated movements performed at three different speeds. In line with *Chapter Five,* an additional objective was to assess the level of trunk muscle co-activation during these movements. As well as any potential correlations between measures of kinematic variability and levels of trunk muscle co-activation, pain intensity, disability, physical activity and fear of movement in those with CNSLBP. This was mainly to find a suitable comprehensive tool to assess 3D variability of spinal motion, aiming to detect differences in spinal kinematic variability in people with CNSLBP compared to asymptomatic individuals. Specifically by using parameters that are sensitive to change in joint position and orientation, ensuring ease of interpretation and, consequently, facilitating the use of movement variability assessment in clinical settings. It was hypothesised that people with CNSLBP would present with modified kinematic variability during repetitive movements when compared with asymptomatic individuals and that speed of movement would influence these differences considering the conclusions of recent reviews on the effects of LBP on kinematic variability (Alsubaie et al., 2023a, Saito et al., 2021).

6.3 Methods

6.3.1 Design and setting

This cross-sectional study has the same ethical approval as *Chapter Five* by the Ethics Committee of the University of Birmingham (Approval number: ERN_19-1862: **Appendix 8**) and conducted according to the Declaration of Helsinki. All participants attended one laboratory session and provided written informed consent. The study is reported in line with the STROBE guidelines (von Elm et al., 2008).

6.3.2 Participants

Thirty-nine volunteers including 20 asymptomatic individuals and 19 with CNSLBP were recruited. The required sample size was estimated based on a previous study evaluating parameters of the HA for the cervical spine in people with and without chronic neck pain (Alsultan et al., 2019). The sample size was calculated using G*Power 3.1.9.4 based on an α of 0.05, a power of 0.80 and a moderate effect size of (f) 0.23. For each group being measured across nine observations during different test conditions, at least 17 participants were needed per group to detect a significant effect. We aimed to recruit 20 participants in each group to account for the potential loss of participants.

6.3.3 Inclusion and exclusion criteria

Inclusion for asymptomatic individuals and exclusion criteria for both groups were identical to those described in *Chapter Five*. In addition, individuals with CNSLBP were considered for the study if their LBP have persisted for at least 3 months and resulted in pain on at least half the days in the past 6 months. They were excluded if their back pain was attributed to a specific cause.

6.3.4 Questionnaires

Similar to *Chapter Five*, anthropometric and IPAQ Questionnaire data were collected from both groups at the beginning of the session. Participants with CNSLBP were required to complete several additional baseline questionnaires including the ODI to assess perceived disability (Fairbank and Pynsent, 2000, Vianin, 2008). An 11-point Pain Numeric Rating Scale (0-10) (PNRS) was used to assess current back pain intensity at the time of testing, and pain over the prior week and month as well as on completion of the session (Breivik et al., 2008).

Participants were asked to complete the FABQ to assess potential fear of movement and this patient-reported outcome measures has excellent reliability for people with chronic LBP (George et al., 2010). In addition, a self-rating scale of depression, anxiety and stress was used (DASS-21) (Crawford and Henry, 2003, Lovibond and Lovibond, 1995).

The remainder of the study, including the collection of data for trunk 3D kinematics, EMG, experimental procedures, and data processing, followed the same protocol as outlined in *Chapter Five*.

6.3.5 Statistical analysis

Normal distribution of the data was confirmed using a Shapiro–Wilk test and thus parametric tests were applied. Descriptive statistics were used to describe the anthropometrics data and questionnaire scores expressed as mean and standard deviation (SD). Separately for each spinal segments (i.e., thoraco-lumbar, lumbo-sacral), two-way mixed Analysis of Variance (ANOVA) were conducted to compare main and interaction effects of group (control vs. CNSLBP), and speed of motion (within-subject factors). Whenever main effects were identified by ANOVA, Bonferroni post-hoc test was used for pairwise comparisons. Additionally, differences in velocity, ROM, and

trunk muscles co-activation (TMCf mean) were evaluated using the same analysis based on the main effect of group. Effect size has been reported where appropriate with ANOVA results, in the format of ηp^2 values (Lakens, 2013).

Pearson correlation was used to evaluate associations between the HA parameters and trunk muscles co-activation (TMCf mean), and reported clinical features in people with CNSLBP. Statistical analysis was performed using SPSS 29 (IBM, USA) with an alpha level set at $\alpha=0.05$. For all variables, an average was computed across the three trials.

6.4 Results

Participant characteristics are presented in **Table 6.1.** No significant differences were found between groups ($p>0.05$) for age, weight nor height. The CNSLBP group reported mild current pain intensity and presented with minimal disability.

Table 6.1: **Participant characteristics and results of patient-reported outcome measures as Mean±SD**

ODI: Oswestry Disability Index, **PNRS:** Pain Numeric Rating Scale, **FABQ:** Fear Avoidance Beliefs Questionnaire.

	Control group (N=20; ♂: 10, ♀ 10)	**CNSLBP group (N=19; ♂: 9, ♀ 10)**	***p*-value**
Age (years)	28.23±4.36	29.93±5.24	$p=0.278$
Weight (kg)	71.31±15.95	71.23±17.16	$p=0.976$
Height (m)	1.71±0.09	1.66±0.11	$p=0.122$
IPAQ	65.00% High	36.84% High	-
ODI (%)	-	16.05±8.56	-
Current PNRS	-	3.26±1.69	-
After session PNRS	-	3.53±2.50	-
Week prior PNRS	-	4.21±2.07	-
Month prior PNRS	-	4.15±1.74	-

FABQ- work scale	-	9.52±7.22	-
FABQ- physical scale	-	10.47±4.53	-
FABQ- total	-	25.00±11.19	-
DASS-21 Depression score	-	2.94±2.75	-
DASS-21 Stress score	-	4.21±3.50	-
DASS-21 Anxiety score	-	2.36±2.36	-

6.4.1 Angular displacement and velocity

The ROM of each movement cycle for both groups are presented in **Table 6.2**. People with CNSLBP presented with similar (p>0.05) ROM compared to asymptomatic individuals There was no significant main effect of group (p>0.05) in terms of the velocity of their movement.

Table 6.2: **Mean±SD of the combined spinal ROM (i.e., thoracolumbar and lumbosacral) as well as movement velocity in all test conditions.**

ηp^2: Eta-squared, ***p** < 0.05; ****p** < 0.005; ***** p** < 0.001.

			Fast	**Self-selected speed**	**Slow**	**Main effect of group**	**F**	**ηp^2**
Flexion/ Extension	**Flexion ROM (°)**	**Control**	38.76±6.25	38.15±4.52	37.69±5.94	p=0.135	2.3	0.059
		CNSLBP	35.63±6.98	36.49±5.39	35.21±7.41			
	Extension ROM (°)	**Control**	17.11±5.99	16.49±4.36	15.76±5.32	p=0.222	1.5	0.040
		CNSLBP	14.06±6.33	14.77±5.92	14.94±4.65			
	Velocity (mm/s)	**Control**	569.40±118.2	502.98±105.2	396.92±88.4	p=0.469	0.4	0.013
		CNSLBP	566.08±112.6	550.99±107.8	409.56±67.4			
Rotation	**Rt. ROM (°)**	**Control**	28.22±2.82	28.02±2.45	28.11±2.87	p=0.135	2.3	0.059
		CNSLBP	27.13±2.05	26.96±2.85	26.71±2.15			
	Lt. ROM (°)	**Control**	28.37±2.85	28.31±2.60	28.23±2.99	p=0.173	1.9	0.050
		CNSLBP	27.50±2.26	27.14±2.47	26.95±2.00			
	Velocity (mm/s)	**Control**	369.69±79.1	378.04±78.09	244.85±54.7	p=0.050	4.1	0.101
		CNSLBP	385.30±82.4	428.54±102.4	298.40±81.3			
Side bending	**Rt. ROM (°)**	**Control**	22.27±7.46	22.27±9.07	24.73±8.34	p=0.124	2.4	0.063
		CNSLBP	18.95±9.70	18.75±8.14	19.98±10.49			
	Lt. ROM (°)	**Control**	22.30±7.44	22.27±9.21	24.75±8.62	p=0.149	2.1	0.055
		CNSLBP	18.95±9.72	19.23±8.23	20.27±10.28			
	Velocity (mm/s)	**Control**	414.18±108.5	420.61±110.6	295.03±77.42	p=0.521	0.4	0.011
		CNSLBP	428.63±106.8	447.36±84.6	311.17±94.14			

6.4.2 Kinematic variability of movement

All HA parameters measured for both groups during all test conditions are presented as mean and standard deviation in **Figure 6.1 and Table 6.3.**

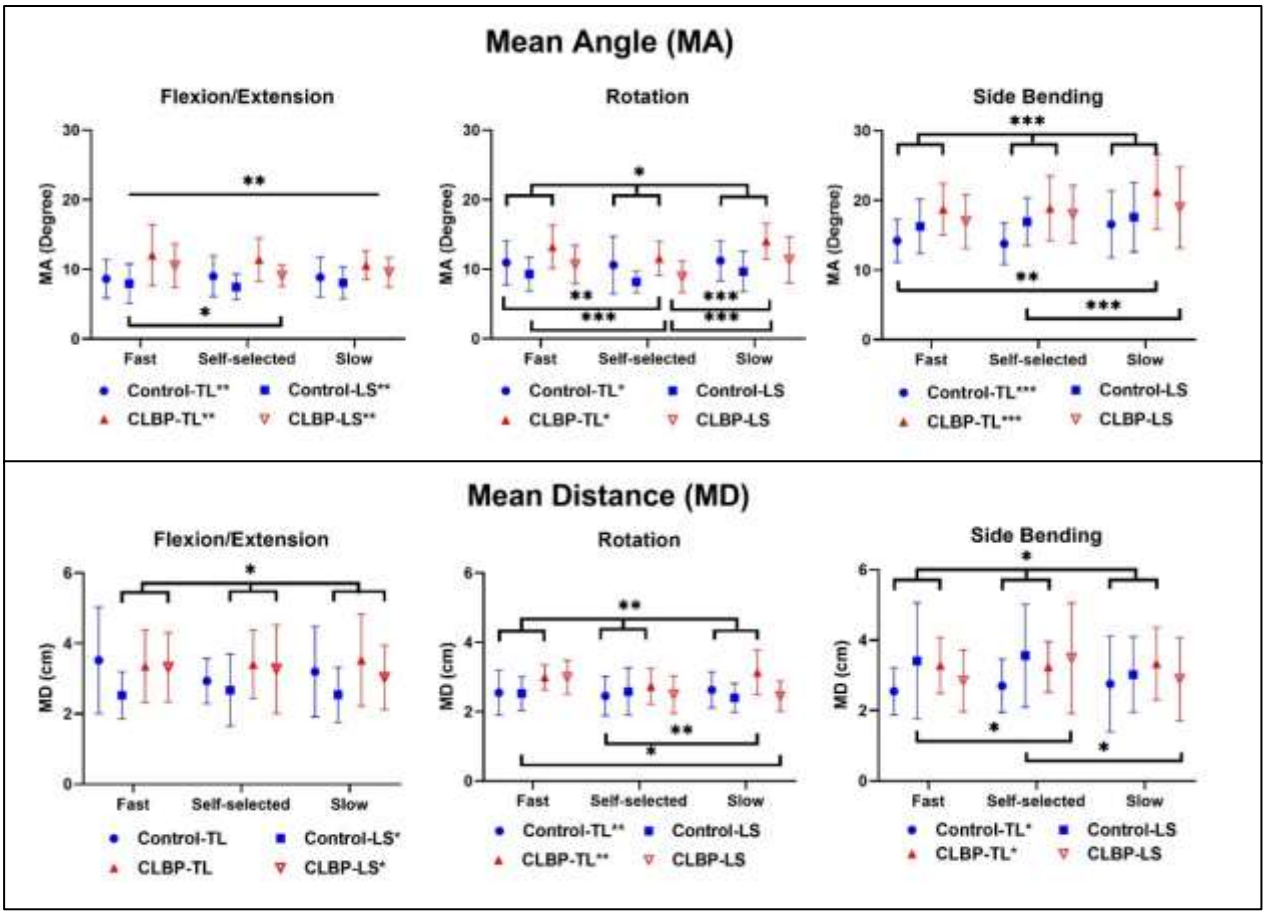


Figure 6.1: **Kinematic variability differences between people with and without CNSLBP based mean and standard division (SD) of the helical axis parameters (HA)**

Mean angle (**MA**) and mean distance (**MD**); between the thoracolumbar (**TL**) and lumbosacral (**LS**) segments. Statistically significant difference; *$\boldsymbol{p}$ < 0.05; **$\boldsymbol{p}$ < 0.005; *** $\boldsymbol{p}$ < 0.001; upper lines represent statistically significant differences between groups while the lower lines represent statistically significant difference between speed conditions.

Flexion/Extension cycles

People with CNSLBP displayed a higher MA for the thoracolumbar segment during flexion/extension cycles *(p*=0.005). However, the MA did not vary significantly (*p*=0.371) across different speeds and was not dependent on the interaction between group and speed (*p*=0.174). The lumbosacral MA was higher for those with CNSLBP compared to the asymptomatic individuals (*p*=0.007) and varied significantly (*p*=0.022) across different movement speeds, with higher MA during fast speed compared to the self-selected speed (p=0.058, mean dif.(95% CI)=0.938, (-0.024;1.901)). However, this was not dependent on the interaction between group and speed (*p*=0.180).

The MD measured at the thoracolumbar segment was not significantly (*p*=0.483) different between groups, did not vary with speed (*p*=0.362) and was not dependent on the interaction between group and speed (*p*=0.223). The MD measured at the lumbosacral segment was significantly larger for those with CNSLBP compared to asymptomatic individuals (*p*=0.012), however, there was no effect of speed (*p*=0.521) and no interaction between group and speed (*p*= 0.650).

Rotation Cycles

People with CNSLBP presented with higher MA for the thoracolumbar segment (*p*=0.039). For both groups, the MA varied with speed (*p*<0.001) with a higher MA during movements performed at the slow speed compared to self-selected speed (*p*<0.001, mean dif. (95% CI)=1.55, (0.760;2.35)) and during the movements performed at the fast speed compared to self-selected speed (*p*=0.007, mean dif.(95% CI)=1.019, (0.233;1.80)). The MA for the thoracolumbar segment was also dependent on the speed and group interaction (*p*=0.010). The lumbosacral MA did not differ

between groups (p=0.089). However, the lumbosacral MA did vary with speed (p<0.001) with a higher values of the MA were observed during slow movements compared to the self-selected speed (p=0.000, mean dif.(95% CI)=1.95, (0.978;2.93)) and during fast movements compared to the self-selected speed (p=0.000, mean dif.(95% CI)=1.43, (0.645;2.23)). Nevertheless, there was no interaction between speed and group (p=0.370).

People with CNSLBP displayed larger thoracolumbar MD compared with asymptomatic individuals (p=0.007) which varied across movement speed (p=0.009) with higher thoracolumbar MD during the slow speed condition compared to the self-selected speed (p=0.003, mean dif.(95% CI)=0.288, (0.086;0.490)). However, there was no interaction between speed and group (p=0.431). The lumbosacral MD did not differ between groups (p=0.329). However, the lumbosacral MD did vary across speed (p=0.011) with larger MD during faster movements compared to those performed at the slow speed (p=0.018, mean dif.(95% CI)=0.339, (0.046;0.631)). In addition, there was a speed by group interaction (p=0.035) which showed higher MD values for the CNSLBP group compared with asymptomatic individuals during the fast speed movement condition (p=0.044, mean dif.(95% CI)=0.47, (0.014;0.927)).

Side Bending Cycles

People with CNSLBP displayed higher thoracolumbar MA during side bending cycles compared with asymptomatic individuals (p<0.001). For both groups, MA varied with speed (p<0.001) with a higher thoracolumbar MA during the slow speed condition compared to the faster speed condition (p<0.001, mean dif.(95% CI)=2.43, (0.844;4.02)) and during movements at the slower speed compared to self-selected speed (p<0.001, mean dif.(95% CI)=2.57, (1.12;4.02)). However, there was no interaction between speed and group (p=0.837). The lumbosacral MA did

not differ between groups (p=0.346). In addition, the lumbosacral MA did not vary with speed (p=0.107), and was not dependent on the interaction between group and speed (p=0.882).

People with CNSLBP displayed a larger thoracolumbar MD compared with asymptomatic individuals (p=0.012), however, there was no effect of speed (p=0.648) nor an interaction between group and speed (p= 0.748). In contrast, the lumbosacral MD did not differ between groups (p=0.507). However, the lumbosacral MD did vary with speed (p=0.008) with larger MD values observed for the self-selected speed condition compared to movements at the faster speed (p=0.049, mean dif.(95% CI)=0.397, (0.001;0.792)) and during the self-selected speed compared to the slower speed (p=0.027, mean dif.(95% CI)=0.563, (0.051;1.07)). Nevertheless, there was no interaction between speed and group (p=0.302).

Table 6.3: **Results of the mixed ANOVA and Bonferroni post hoc multiple comparisons based on main effect of group**

Mean angle (**MA**) and mean distance (**MD**); between the thoracolumbar (**TL**) and lumbosacral (**LS**) segments. Statistically significant difference; ***p** < 0.05; ****p** < 0.005; ***** p** < 0.001; **ηp^2**: Eta-squared, **95% CI:** 95% confidence interval

Plane of Motion	Spinal Segment	HA	Speed	Group Effect	Speed Effect	Group*Speed Interaction Effect	Groups	Mean±SD	Mean Difference (95% CI)
Flexion/ Extension	**TL**	**MA (°)**	Fast	p=0.005* F= 8.7 ηp^2=0.191	p=0.371 F= 0.99 ηp^2=0.026	p=0.174 F= 1.8 ηp^2=0.047	Controls	8.62°±2.7°	2.50 (0.79, 4.22)
							CLBP	12.03°±4.3°	
			Self-selected				Controls	9.01°±2.9°	
							CLBP	11.40°±3.1°	
			Slow				Controls	8.87°±2.8°	
							CLBP	10.59°±2.1°	
		MD (cm)	Fast	p=0.483 F= 0.503 ηp^2=0.013	p=0.362 F= 1.008, ηp^2=0.027	p= 0.223 F= 1.542 ηp^2=0.040	Controls	3.52±1.5	0.21 (-0.39, 0.81)
							CLBP	3.35±1.0	
			Self-selected				Controls	2.93±0.6	
							CLBP	3.40±0.9	
			Slow				Controls	3.19±1.2	
							CLBP	3.52±1.3	
	LS	**MA (°)**	Fast	p=0.007*	p=0.022*	p=0.180	Controls	7.95°±2.8°	1.88 (0.53, 3.23)
							CLBP	10.5°±3.1°	

			Self-selected	F= 8.0 ηp^2=0.178	F= 4.6 ηp^2=0.111	F= 1.8 ηp^2=0.047	Controls	7.49°±1.8°	
							CLBP	9.09°±1.5°	
			Slow				Controls	8.06°±2.2°	
							CLBP	9.5°±2.1°	
		MD (cm)	Fast	*p*=0.012*	*p*=0.521	*p*= 0.650	Controls	2.53±0.6	0.62 (0.14, 1.11)
							CLBP	3.32±0.9	
			Self-selected	F= 6.92 ηp^2=0.158	F=0.658 ηp^2=0.017	F= 0.433 ηp^2=0.012	Controls	2.67±1.0	
							CLBP	3.27±1.2	
			Slow				Controls	2.54±0.7	
							CLBP	3.03±0.8	
Rotation	**TL**	**MA (°)**	Fast	*p*=0.039*	*p*<0.001***	*p*=0.010*	Controls	10.96°±3.1°	2.00 (0.10, 3.90)
							CLBP	13.24°±3.1°	
			Self-selected	*F=4.58* *ηp^2=0.110*	*F=13.87* *ηp^2=0.273*	*F=5.03* *ηp^2=0.120*	Controls	10.61°±4.1°	
							CLBP	11.55°±2.4°	
			Slow				Controls	11.24°±2.8°	
							CLBP	14.03°±2.5°	
		MD (cm)	Fast	*p*=0.007*	*p*=0.009*	*p*=0.431	Controls	2.55±0.6	0.41 (0.12, 0.69)
							CLBP	2.99±0.3	
			Self-selected	F=8.15 ηp^2=0.181	F=5.22 ηp^2=0.124	F=0.838 ηp^2=0.022	Controls	2.45±0.5	
							CLBP	2.73±0.5	
			Slow				Controls	2.62±0.5	
							CLBP	3.13±0.6	
	LS	**MA (°)**	Fast	*p*=0.089	*p*<0.001***	*p*=0.370	Controls	9.31°±2.4°	1.26 (-0.20, 2.74)
							CLBP	10.70°±2.7°	
			Self-selected	F=3.04 ηp^2=0.076	F=17.63 ηp^2=0.323	F=0.99 ηp^2=0.026	Controls	8.20°±1.5°	
							CLBP	8.94°±2.2°	
			Slow				Controls	9.69°±2.8°	
							CLBP	11.37°±3.3°	
		MD (cm)	Fast	*p*=0.329	*p*=0.011*	*p*=0.035*	Controls	2.52±0.5	0.14 (-0.14, 0.43)
							CLBP	2.99±0.9	
			Self-selected	F= 0.977 ηp^2=0.026	F=5.08 ηp^2=0.121	F=3.6 ηp^2=0.090	Controls	2.57±0.7	
							CLBP	2.49±0.5	
			Slow				Controls	2.40±0.4	
							CLBP	2.44±0.4	
Side Bending	**TL**	**MA (°)**	Fast	*p*<0.001***	*p*<0.001***	*p*=0.837	Controls	14.22°±3.1°	4.77 (2.38, 7.17)
							CLBP	18.74°±3.6°	
			Self-selected	*F=16.30* *ηp^2=0.306*	*F=13.52* *ηp^2=0.268*	*F=0.143* *ηp^2=0.004*	Controls	13.79°±2.9°	
							CLBP	18.89°±4.6°	
			Slow				Controls	19.56°±4.8°	
							CLBP	21.26°±5.4°	
		MD (cm)	Fast	*p*=0.012*	*p*=0.648	*p*= 0.748	Controls	2.54±0.7	0.62 (0.14, 1.09)
							CLBP	3.28±0.8	
			Self-selected	F=6.93 ηp^2=0.158	F=0.365 ηp^2=0.010	F= 0.226 ηp^2=0.006	Controls	2.07±0.7	
							CLBP	3.24±0.7	
			Slow				Controls	2.75±1.3	
							CLBP	3.33±1.0	
	LS	**MA (°)**	Fast	*p*=0.346	*p*=0.107	*p*=0.882	Controls	16.27°±3.8°	1.06 (-1.19, 3.32)
							CLBP	16.99°±3.8°	
			Self-selected	*F= 0.912* *ηp^2=0.024*	*F= 2.39* *ηp^2=0.061*	*F= 0.097* *ηp^2=0.003*	Controls	16.93°±3.4°	
							CLBP	18.03°±4.1°	
			Slow				Controls	17.59°±4.9°	

							CLBP	18.97°±5.7°	
		MD (cm)	Fast	*p*=0.507	*p*=0.008*	*p*=0.302	Controls	3.41±1.6	0.25 (-1.02, 0.51)
							CLBP	2.84±0.8	
			Self-selected	F= 0.448 ηp^2=0.012	F=5.52 ηp^2=0.130	F=1.20 ηp^2=0.032	Controls	3.56±1.4	
							CLBP	3.48±1.5	
			Slow				Controls	3.02±1.1	
							CLBP	2.89±1.2	

6.4.3 Trunk muscle co-activation

There was no main effect of group (F=1.69, *p*=0.201, ηp^2=0.560) on trunk muscle co-activation (TMCf mean). However, A negative significant correlation was only found between MD and the co-contraction index (TMCf mean) during fast side bending cycles (r= -0.472, *p*=0.041) for the chronic LBP group (**Figure 6.2** and **Table 6.4**).

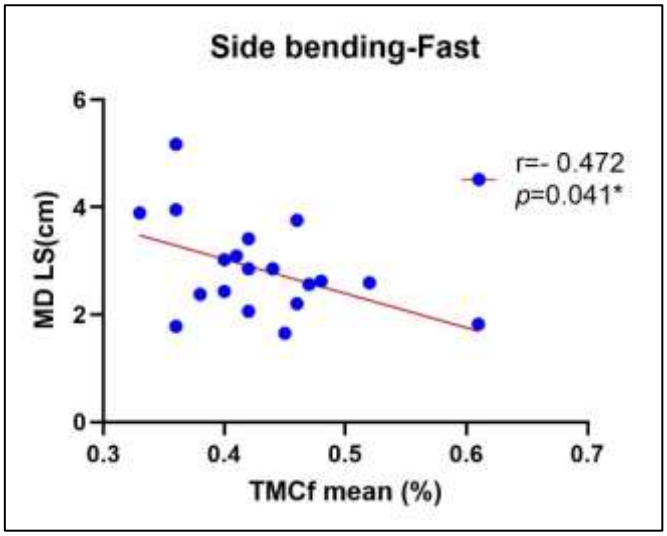


***Figure 6.2*: Correlation between lumbosacral mean distance (LS MD) and trunk muscle co-activation**

Time-varying multi-muscle co-activation function (**TMCf mean**) ***p** < 0.05

Table 6.4: **Correlations between helical axis parameters and trunk muscles co-activation**

Mean angle (**MA**), mean distance (**MD**) in thoracolumbar (**TL**) and lumbosacral (**LS**) segments and co-activation index (time-varying multi-muscle co-activation function TMCf mean) $*\boldsymbol{p} \leq 0.05$.

Test Condition	Helical axis parameter	Correlation coefficient	Sig. (2-tailed)
Flexion/Extension Fast	MA TL	0.049	0.841
	MA LS	-0.070	0.777
	MD TL	-0.269	0.265
	MD LS	0.283	0.240
Flexion/Extension Self-selected speed	MA TL	0.313	0.192
	MA LS	0.176	0.472
	MD TL	0.142	0.561
	MD LS	0.317	0.186
Flexion/Extension Slow	MA TL	0.200	0.411
	MA LS	-0.179	0.464
	MD TL	-0.109	0.656
	MD LS	-0.072	0.770
Rotation Fast	MA TL	0.284	0.239
	MA LS	-0.175	0.475
	MD TL	-0.023	0.924
	MD LS	0.195	0.424
Rotation Self-selected speed	MA TL	0.010	0.966
	MA LS	-0.097	0.693
	MD TL	0.019	0.938
	MD LS	-0.412	0.080
Rotation Slow	MA TL	-0.008	0.975
	MA LS	-0.405	0.085
	MD TL	0.096	0.695
	MD LS	-0.192	0.430
Side bending Fast	MA TL	0.219	0.368
	MA LS	-0.311	0.195
	MD TL	-0.225	0.355
	MD LS	-0.472*	0.041*
Side bending Self-selected speed	MA TL	-0.014	0.955
	MA LS	-0.437	0.061
	MD TL	-0.224	0.357
	MD LS	-0.273	0.258
Side bending Slow	MA TL	-0.237	0.328
	MA LS	-0.324	0.176
	MD TL	-0.293	0.223
	MD LS	-0.373	0.116

6.4.4 Correlations between kinematic variability and CNSLBP clinical features

The correlations between the measures of kinematic variability and all clinical characteristics for those with CNSLBP were analysed, however, only significant findings are presented in **Table 6.5.** Significant correlations were found for MA and MD at both thoracolumbar and lumbosacral segments with the following variables: PNRS ODI, and FABQ.

Table 6.5: **Correlations between clinical characteristics and helical axis parameters (HA) for those with CNSLBP**

Mean angle (**MA**) and mean distance (**MD)**; between thoracolumbar (**TL**) and lumbosacral (**LS**) segments. ***p*** < 0.05; ****p*** < 0.005; ***** *p*** < 0.001.

Questionnaires	Test Condition	HA parameter	Correlation coefficient	Sig. (2-tailed)
Current PNRS	Flexion/Extension Fast	MA LS	-0.510	0.026*
	Rotation Fast	MA LS	-0.541	0.017*
	Side bending Self-selected speed	MD TL	-0.595	0.007**
Prior week PNRS	Rotation Fast	MD TL	-0.461	0.047*
	Rotation Slow	MD LS	-0.599	0.007**
Prior month PNRS	Rotation Fast	MD TL	-0.637	0.003**
	Rotation Slow	MD LS	-0.687	0.001**
ODI	Rotation Fast	MA LS	-0.456	0.050*
FABQ work scale	Side bending Self-selected speed	MA TL	-0.531	0.019*
	Side bending Self-selected speed	MD TL	-0.539	0.017*
	Side bending Slow	MA TL	-0.491	0.032*
FABQ physical scale	Flexion/Extension Self-selected speed	MA TL	0.496	0.031*
	Flexion/Extension Self-selected speed	MD TL	0.586	0.008**
FABQ total	Side bending Self-selected speed	MD TL	-0.619	0.005**

6.5 Discussion

This study is the first to quantify the parameters of HA during active trunk movements in people with CNSLBP compared to asymptomatic individuals. The HA parameters were estimated using 15 consecutive cycles of trunk movements in three planes of motion. People with CNSLBP presented with higher values of HA parameters regardless of the speed or plane of movement indicating higher spinal kinematic variability, especially thoracolumbar segment, while performing repetitive trunk movements.

It is well established that people with CNSLBP commonly present with different movement characteristics such as reduced multi-segment spinal ROM, slower movement, and greater muscle activation (Alsubaie et al., 2021a, Laird et al., 2019, Shum et al., 2005, Swain et al., 2019). Unique to this study, we have applied measures of the HA to show that people with CNSLBP also move with different kinematic variability of spinal regions. Kinematic variability was quantified for the thoracolumbar and lumbosacral spine segments during repetitive trunk motion using the two proposed parameters of HA, i.e., the MD and MA (Cescon et al., 2014); higher values of these parameters indicate higher variability (Alsultan et al., 2019, Cescon et al., 2019). Spinal kinematic variability was higher for those with CNSLBP as revealed by differences in MA and MD parameters, especially for the thoracolumbar segment. In contrast, kinematic variability at the lumbosacral region only differed during flexion/extension cycles.

In addition, slower speed cycles significantly increased kinematic variability, especially at the thoracolumbar region, and this occurred regardless of the plane of movement examined. This negative linear relationship between movement variability and movement speed was observed previously in people with CNSLBP during repetitive flexion–extension movements (Asgari et al., 2015). However, lumbosacral kinematic variability became higher at a faster speed, which could be an attempt to find a suitable path of movement to alleviate pain during faster movements.

Different spinal kinematic variability was previously observed in people with CNSLBP using other statistical tools including linear and non-linear metrics. For example, during repetitive functional tests, the variability of lumbar movement was found to be increased in people with CNSLBP with greater LBP intensity, as determined by decreased determinism (Bauer et al., 2015). Similarly, during sit-to-stand-to-sit task, people with CNSLBP showed less coordinated and a more variable lumbar movement pattern (Ippersiel et al., 2018). Furthermore, other studies have described the variability of lumbar movement as more irregular motions in people with CNSLBP compared to acute LBP using the irregularity quantification analysis (Williams et al., 2013). Nevertheless, some studies were unable to detect any differences in kinematic variability when people have CNSLBP (Asgari et al., 2017, Chehrehrazi et al., 2017, Graham et al., 2014, Pranata et al., 2018, Shojaei et al., 2017). In terms of variability metrics and movement quality, the MA and MD parameters offer a detailed understanding of movement variability, particularly in dynamic contexts where movement patterns evolve over time. By considering both spatial and temporal aspects, they provide a comprehensive evaluation of movement quality. In contrast, meanSD, as measured in *Chapter Three*, provides a limited assessment of variability at each time point, focusing solely on the amount of variation.

Previously, higher variability of knee joint movement was observed for elderly people compared to young healthy adults; this was revealed by higher MA and MD during walking for the older adults (Temporiti et al., 2020). As another example, young healthy adults showed lower shoulder movement variability, revealed by lower MA and MD compared to older adults (Temporiti et al., 2019). However, for spinal movements, the HA dispersion has only been evaluated for the cervical spine, and this work revealed reduced MA and MD parameters in the presence of chronic neck pain (Alsultan et al., 2019). In contrast, our study has revealed an increase in kinematic variability in the presence of CNSLBP. This difference could be attributed to the higher DOFs

available at the cervical spine compared to the thoracic and lumbar segments which have limited ROM. Thus, people with chronic neck pain may have reduced their movement variability as a protective mechanism whereas, people with CNSLBP adopted a control strategy in order to perform repetitive movements with more motor solutions to possibly be able to reduce their pain or minimise fatigue. Therefore, it is imperative to integrate assessments of movement variability, such as incorporating measures like the HA, into routine clinical assessments to deepen our understanding of patients with spinal pain. By integrating these assessments, clinicians can gain deeper insights to differentiate between functional adaptations, which involve beneficial adjustments in the movement variability aimed to enhance sensory generation, and maladaptive adaptations, which may be associated with impaired motor performance or increased injury risk. This not only leads to a better diagnoses and tailored treatment plans but also provides an easy and accessible tool for communication among healthcare professionals supporting collaborative decision-making to improve rehabilitation outcomes.

6.5.1 Correlations between kinematic variability with trunk muscle co-activation and clinical features

The decision to record more muscles in this study was influenced by the findings and methodologies in *Chapters Three* and *Four*, highlighting the importance of comprehensive muscle activity assessment to enhance our understanding of motor control patterns associated with CNSLBP. However, despite this methodological refinement, our investigation did not reveal significant differences in trunk muscle co-activation between individuals with CNSLBP and asymptomatic individuals. While no differences were observed in term of trunk co-activation in people with CNSLBP compared to asymptomatic individuals, higher trunk muscle co-activation was associated with lower kinematic variability during repetitive side bending movements. This

pattern of motor control in people with LBP has been referred to as tight control, and is possibly a strategy to avoid pain, injury, or anticipation of such threats (van Dieën et al., 2019b). However, this was not evident during all test conditions which limits confidence in this observation. Further studies are warranted to corroborate this observation.

Although an association was not observed during all test conditions, lower spinal kinematic variability was associated with higher levels of LBP intensity, disability, and fear of movement. Thus, despite the higher kinematic variability observed overall for those with CNSLBP, those with higher levels of pain, disability, and fear of movement exhibit the lowest kinematic variability during repetitive trunk movements. While individuals with CNSLBP exhibit significantly greater kinematic variability compared to those without pain, their HA values show relatively similar patterns. Thus, relying solely on HA parameters to distinguish between the two groups appears to be an area that requires further investigation. Therefore, questionnaire-based assessments were carried out to evaluate participants' psychological and clinical characteristics. Additionally, subjective observations were conducted during the experiment to evaluate the presence of pain and the intensity.

The finding that individuals with CNSLBP, particularly those with higher levels of pain, disability, and fear of movement, exhibit lower kinematic variability supports the previously proposed hypothesis concerning stereotypical behaviour of trunk movement, particularly the phenotype characterised by heightened activation of trunk muscles to provide tight control over lumbar movement which subsequently reduces movement variability (van Dieën et al., 2019a, van Dieën et al., 2019b). This hypothesis proposed that the adaptive motor control changes in response to LBP are the outcome of reinforcement learning process predicting an initial increase in variability during the acute stage of pain, followed by a reduced variability resulting potentially in negative long-term consequence (van Dieën et al., 2017). However, this pattern was not observed in

the individuals with chronic LBP in the current study. Instead, our recruited participants exhibited increased movement variability without a corresponding increase in trunk muscle activation compared to asymptomatic individuals. This is possibly due to the observed mild levels of pain and disability. This observation may suggest that the reinforcement learning process, characterised by increased variability, may persist even during the chronic stage of LBP and could be more related to the levels of pain intensity and disability rather than the chronicity of the symptoms. Furthermore, fear of movement is previously reported to be positively but weakly associated with trunk stiffness (Karayannis et al., 2013).

Most correlations with helical axes parameters show a negative trend, with FABQ being no exception, except for FABQ with MA and MD in flexion/extension. This observation aligns with the positive association between FABQ and lumbar meanSD noted in *Chapter Three* during the flexion/extension task. These findings suggest that the type of task and the plane of movement may influence the direction of correlations between spinal kinematic variability and psychological features. However, differences between populations, including variations in pain levels, fear of movement, and disability, as well as discrepancies in kinematic models and analysis methods for spinal kinematic variability, emphasise the diverse contexts in which these correlations were observed. However, these findings further support the interaction between physical and psychological features of CNSLBP, although further research is required to better understand the associations observed in the current study.

6.5.2 Methodological considerations

As this study represents the first investigation into measuring HA of thoracolumbar and lumbosacral segments, careful consideration was given to the methodological approach by

conducting the experiment separately in each plane. Although measuring the HA in 3D movements might seem advantageous, it could introduce additional dispersion into the HA parameters, potentially leading to less accurate results. Future research may explore the possibility of measuring HA in 3D movements. However, it is crucial to ensure that such advancements do not introduce higher dispersion and movement variability than anticipated, which could compromise the accuracy of the results.

The MA and MD parameters of the HA have been shown to be reliable during active movements of the cervical spine (Barbero et al., 2017). However, the reliability of the measures have not been investigated for other spinal levels, and this may differ especially for people with spinal pain. Moreover, the pelvic movement was not constrained although any unnecessary pelvic movements was limited by asking the participants to perform the tasks while sitting.

Considering the exploratory nature of the correlational analysis and the extensive number of observations examined, it is essential to acknowledge the potential influence of chance on the observed results. However, the assessment of correlations between kinematic variability and trunk muscle co-activation were only assessed within each individual group. Future research might use mixed models that incorporate co-contraction values with group as a fixed factor. This approach would allow for a more comprehensive analysis, considering both within-group and between-group variability, to better understand the relationship between co-contraction patterns and spinal kinematic variability.

6.6 Conclusion

People with CNSLBP demonstrate greater kinematic variability during active spinal movements, irrespective of the speed or plane of movements. This may reflect an adaptive

behaviour to long-lasting pain. However, the variability of movement is less for those with higher levels of disability and pain intensity. In addition, people with a higher fear of movement show the lowest kinematic variability of their lumbar spine.

CHAPTER 7

GENERAL DISCUSSION

7.1 Summary of findings

The main aim of this thesis was to enhance the understanding of motor adaptations in people with CNSLBP, specifically, kinematic variability differences, and how trunk muscle co-activation patterns together with the presented clinical features might be related to the observed differences in the variability of spinal movement compared to asymptomatic individuals. *Chapter One* provided an overview on LBP highlighting that it is a challenging clinical condition that impacts the quality of life and that it is the main cause of years lived with disability (Ferreira et al., 2023, Hartvigsen et al., 2018, Wu et al., 2020). The chapter also provided a comprehensive background on motor control during spinal movements and how it is widely acknowledged that people with chronic LBP move differently than those without pain (Hodges and Tucker, 2011, van Dieën et al., 2019b) due to several identified neuromuscular adaptations in response to spinal pain (Devecchi et al., 2021). The rationale behind the importance of investigating trunk motor adaptations with the presence of chronic LBP were highlighted in *Chapter One* and within this context, spinal kinematic variability emerged as an area of research that warrants further investigation and thus was the focus of this thesis.

Chapter Two presented a systematic review which aimed to achieve Objective One of the thesis; to synthesise the evidence on whether spinal kinematic variability is different in people with CNSLBP during repetitive trunk movements when compared to asymptomatic individuals (Alsubaie et al., 2023a). The conducted systematic review identified four different tasks that were

commonly tested to investigate spinal kinematic variability. Although this review categorised the evidence for better interpretation, according to the tasks performed, the selection of the used metrics (i.e., linear and non-linear measures) within each subgroup played a critical role in understanding differences in movement variability. Despite the substantial heterogeneity noted within the literature, our review was conducted with rigorous methodology outlined in a predefined and published protocol, focusing on a carefully specified population with defined characteristics. While meta-analysis was not feasible due to the heterogeneous nature of the studies, we presented our findings quantitatively using forest plots to complement the narrative synthesis. The systematic review showed that people with CNSLBP exhibit different kinematic variability during trunk repetitive movements compared to asymptomatic individuals. However, the direction of these differences was not consistent across studies, and the level of evidence supporting these observations was very low, questioning the confidence in the estimate of results of these studies. This systematic review revealed the importance of standardising terminology and metrics for assessing variability of spinal movements and emphasised the need for future research to consider the conceptual differences between different metrics.

In light of the findings from the systematic review, *Chapter Three* presented a cross-sectional observational study that investigated trunk motor control in people with CNSLBP compared to asymptomatic individuals during a novel real-time tracking task to test spinal kinematic variability with varying speed of motion (Alsubaie et al., 2021a). Movement variability was analysed while participants executed repetitive trunk movements in the sagittal plane following visual feedback. Additionally, it is worth noting that real-time feedback on kinematics is less utilised in research, likely due to the technical difficulties. However, in this study, we were able to provide such feedback despite these challenges. Additional objectives of this study were to test other aspects of trunk motor control such as the temporal differences between movement of the provided feedback

and the participants' actual trunk motion as well as trunk muscle co-activation. This study addressed Objective Two, and furthermore, this experiment addressed Objective Six, aiming to find potential correlations between spinal kinematic variability and levels of pain intensity, disability and fear of movement in those with CNSLBP. Findings based on this study identified no differences in spinal kinematic variability between people with CNSLBP and asymptomatic individuals, over repeated cycles of a tracking task, however, the degree of lumbar kinematic variability during trunk slow speed movements was associated with the degree of fear of movement in those with CNSLBP, where people with greater fear of movement showed higher degrees of variability. Additionally, people with CNSLBP showed a delay in trunk movement relative to asymptomatic participants while tracking the real-time feedback. Yet, it remained uncertain how individuals with CNSLBP would adapt their trunk movement, in terms of variability, during a more functional task.

In order to address this, *Chapter Four* reported a cross-sectional observational study investigating a more complex dynamic lifting task (Alsubaie et al., 2023b). The experiment aimed to achieve Objective Three of the thesis; to evaluate if spinal kinematic variability differs in people with CNSLBP when performing a repetitive multi-planar lifting task, simulating a functional task. Objective Six was also addressed in this study by exploring clinical characteristics of those with CNSLBP. This study represents an advancement in the current understanding in the field of movement variability and lifting, as most of the previous studies have explored coordination variability during repetitive lifting tasks in one plane of motion (trunk flexion and extension), and they have failed to identify different kinematic variability patterns in people with CNSLBP compared to asymptomatic individuals. Similar to *Chapter Three*, the same linear metrics (i.e., MeanSD) were used in this study to measure spinal kinematic variability in three planes of motion. Those with CNSLBP performed the loaded lifting task with the same trunk ROM as asymptomatic

individuals, however, they showed a different motor control strategy by executing the lifting task with higher cycle-to-cycle kinematic variability in both thoracic and lumbar segments of the spine. While the effect sizes varied from moderate to large, it was still uncertain whether this observation had meaningful clinical implications. Thus, it remained critical to explore a new sensitive metric for describing kinematic variability in spinal movement.

Therefore, *Chapter Five* was an experimental single-group and repeated measures study which aimed to examine recently proposed parameters of the HA as a novel measure for spinal kinematic variability during repetitive trunk movements (Alsultan et al., 2019, Alsultan et al., 2020, Barbero et al., 2017). The study addressed Objective Four of the thesis to test HA parameters between three spinal segments (thoracic, lumbar, and sacral) when asymptomatic volunteers engaged in repetitive uniplanar trunk movements, varying both the plane and speed of motion. An additional objective was to evaluate the extent of trunk muscle co-activation during these movements and understand how it might correlate with the degree of kinematic variability. This study revealed that HA parameters are sensitive to changes in movement plane and movement speed. Notably, a greater dispersion of these parameters was observed during trunk side bending movements, particularly at slower speeds. Moreover, rotational movements displayed higher levels of trunk muscle co-activation, accompanied with lower kinematic variability, as well as an association between the degree of kinematic variability and trunk muscle co-activation. Therefore, the use of these parameters to describe trunk kinematic variability and stability may provide new perspectives on trunk motor control strategies and their specific adaptations in people with CNSLBP.

Chapter Six, presented an observational cross-sectional study, focused to achieve Objective Five of the thesis, examining spinal kinematic variability in people with CNSLBP during trunk repetitive movements using the same HA parameters presented in *Chapter Five*. In addition to Objective Six of the thesis, correlations between kinematic variability and trunk muscle co-activations were also

investigated in this study. People with CNSLBP presented with greater kinematic variability in thoracic and lumbar spinal levels during active trunk movements, regardless of the speed or plane of these movements. Nevertheless, those with higher levels of pain intensity display reduced movement variability. Moreover, people with a higher fear of movement demonstrate the lowest spinal kinematic variability. This possibly reflects an adaptive behaviour to long-lasting pain.

Finally, this concluding chapter (*Chapter Seven*), aims to summarise the key findings of this thesis, draw conclusions, document the strengths and limitations of the work presented, and discuss clinical implications and suggestions for future research.

7.2 Spinal kinematic variability in people with CNSLBP

The main question of this thesis revolved around whether people with CNSLBP present with a different spinal movement variability pattern when compared to asymptomatic individuals. A systematic review of existing literature, as presented in *Chapter Two*, revealed the presence of a different kinematic variability pattern in angular displacement of thoracic and lumbar spine during repetitive trunk movements, however, the nature and direction of this difference was not consistent between the reviewed studies (Alsubaie et al., 2023a). In order to explore the direction of the difference, three empirical studies were conducted on people with CNSLBP compared to asymptomatic individuals.

Although the study in *Chapter Three* found a difference in the motor control strategy as a significant delay of trunk movement in people with CNSLBP during the real-time tracking task, no significant difference was observed in terms of variability in their spinal angular displacement (both thoracic and lumbar movements) when compared to asymptomatic individuals (Alsubaie et al., 2021a). The real-time tracking task in this study only tested kinematic variability in the sagittal

plane during repetitive trunk flexion and extension movements. In *Chapter Four,* a loaded multi-planar lifting task was examined to mimic the greater complexity of functional tasks of daily living. The findings of this study showed increased spinal kinematic variability in people with CNSLBP in all planes of motion despite showing the same spinal ROM as asymptomatic individuals during the repetitive lifting movements. Moreover, in *Chapter Six*, using parameters of HA as a novel approach to measure kinematic variability of thoracic and lumbar spine movements, revealed increased spinal kinematic variability in CNSLBP people regardless of the speed or plane of motion while performing repetitive trunk movements. Based on the findings presented in *Chapter Four,* and *Chapter Six,* together with the supporting evidence from *Chapter Two* that confirm the presence of increased spinal kinematic variability in people with CNSLBP compared to asymptomatic individuals, it becomes evident that the observed variability extends across different tasks and planes of motion. These findings align with previous research that has highlighted differences in spinal kinematic variability among individuals with CNSLBP. For instance, Bauer et al. (2015) reported increased lumbar movement variability in individuals with CNSLBP during repetitive functional tests, correlated with greater intensity of LBP. Similarly, Ippersiel et al. (2018) observed less coordinated and more variable lumbar movement patterns during a sit-to-stand-to-sit task in individuals with CNSLBP. Additionally, studies such as Williams et al. (2013) have described lumbar movement as more irregular in individuals with CNSLBP compared to those with acute LBP, using irregularity quantification analysis.

However, it is important to acknowledge the inconsistencies in the literature regarding spinal kinematic variability in individuals with CNSLBP. Some studies, (Asgari et al., 2017, Chehrehrazi et al., 2017, Graham et al., 2014, Pranata et al., 2018, Shojaei et al., 2017) failed to detect significant differences in kinematic variability between individuals with CNSLBP and asymptomatic controls. Furthermore, contrasting findings have been reported in studies examining

trunk kinematics during gait. While van den Hoorn et al. (2012) observed reduced trunk movement variability in individuals with chronic LBP compared to asymptomatic controls, Vogt et al. (2001) reported higher trunk kinematic variability in individuals with chronic LBP during gait. These discrepancies may be attributed to various factors, including differences in study populations, methodologies, and measurement approaches. For instance, the choice of reference frame for analysing trunk kinematics can significantly influence variability outcomes, as demonstrated by the differences between the studies by van den Hoorn et al. (2012) and Vogt et al. (2001).

In this thesis, a similar approach was adopted by utilising both the global frame in *Chapter Three* and the anatomical frame in *Chapter Four* for analysing trunk kinematics. Notably, while *Chapter Three* did not find significant differences in spinal kinematic variability in people with CNSLBP compared with asymptomatic individuals, *Chapter Four* revealed significant differences when using the anatomical frame or relative angles. Therefore, understanding the role of trunk muscles and sensory information processing in different reference frames is essential for accurately interpreting movement variability across studies.

7.3 Exploring possible factors contributing to differences in kinematic variability

An additional aim of this thesis was to explore the potential factors that may explain the difference in movement variability observed in people with CNSLBP. As outlined in *Chapter One*, it is evident that individuals with LBP exhibit different movement patterns compared to those without pain, however, the underlying mechanisms and causes of these differences in motor control remain poorly understood. Commonly, studies on motor control evaluate the outcomes of neural processes by examining patterns of trunk movements and trunk muscle activity, which have yielded

evidence of alternations in neuromuscular control in people with LBP (van Dieën et al., 2019b). These physical factors along with psychological factors have been frequently reported to contribute to LBP, moreover, it has been proposed that there are associations between psychological factors and spinal motor behaviour (Christe et al., 2021).

7.3.1 Examining trunk muscle co-activation

In *Chapter Three*, trunk muscle activity was recorded while repetitively flexing and extending the trunk in both CNSLBP and asymptomatic individuals. People with CNSLBP showed the same individual muscle activity as well as the same co-activation pattern as asymptomatic individuals. The small sample size in this study prevented us from exploring any correlations between trunk muscle recruitment patterns and kinematic variability. Nevertheless, the speed of trunk movement influenced the activation of the OEA muscle, with higher muscle activity at faster speeds (Alsubaie et al., 2021a). This finding was observed in prior research suggesting a strategy to stiffen the trunk as the speed of movement increases (Vera-Garcia et al., 2008, Zoppirolli et al., 2017). However, the findings of this study failed to reveal any differences in the variability of spinal kinematics among individuals with CNSLBP, nor an association between trunk muscle recruitment and kinematic variability.

Trunk muscle co-activation was analysed in *Chapter Five* using an algorithm that can assess simultaneous co-activation of more than two muscles, additionally, this method does not necessitate a-priori classification of the muscles depending on the generated moment (Ranavolo et al., 2015). While this study did not recruit people with CNSLBP, it did reveal correlations in asymptomatic individuals between the parameters of the HA as a measure of kinematic variability and trunk muscle co-activation. The applied mathematical model (TMCf) detected higher levels of trunk co-

activation during repetitive trunk rotational movements, in contrast to the repetitive flexion/extension movements that showed the lowest levels of co-activation. Although correlations were not consistently observed across all test conditions, a common observation was that reduced spinal kinematic variability is accompanied with increased levels of trunk muscle co-activation.

In *Chapter Six*, when trunk muscle co-activation was evaluated in individuals with CNSLBP, the findings confirmed those from *Chapter Three*. Both asymptomatic individuals and people with CNSLBP showed the same muscle co-activation pattern, even though different algorithms were applied in each study to calculate muscle co-activation. This finding was also confirmed in a number of previous studies (Arvanitidis et al., 2021, Martinez-Valdes et al., 2019, Mueller et al., 2017, Mueller et al., 2020). However, the same negative correlation observed in asymptomatic individuals in *Chapter Five* was also observed in *Chapter Six* when people with CNSLBP were tested. The negative correlation suggests that higher trunk muscle co-activation is associated with lower kinematic variability, as indicated by parameters of HA, and vice versa, especially during repetitive side bending movements.

These differences in patterns of trunk motor control have been previously proposed in cases of LBP and categorised to either ‘’tight control’’ or ‘’loose control’’, based on their mechanical outcome (van Dieën et al., 2019b). ‘’Tight control’’ refers to when increased co-activation would increase trunk stiffness and subsequently reduces the movement variability, whereas in ‘’loose control’’, muscular control over spine movement would be diminished due to inhibited muscle activity, resulting in greater movement variability between repeated trials of the same task. Both of these defined phenotypes represent adaptive motor control responses to pain and possibly a strategy to avoid pain or injury, particularly in the short term. The first phenotype may serve to prevent excessive movement and offer stability, while the second phenotype works to reduce high muscle

forces (van Dieën et al., 2019b). However, this finding was not evident during all test conditions in this thesis which limits confidence in this interpretation.

7.3.2 Investigating clinical features

According to a proposed hypothesis, adaptive motor control differences in response to LBP are related to the duration of the LBP symptoms, according to this, the acute stage of LBP is characterised by an increase in variability as an outcome of reinforcement learning process, followed by a decrease in variability during the chronic stage of LBP (van Dieën et al., 2017). In this thesis, all individuals with LBP who showed an increase in movement variability were in the chronic stage. However, they presented with mild intensity of pain and minimal disability at the time of testing for the studies as reported in *Chapter Three*, *Chapter Four* and *Chapter Six*. Therefore, it has been suggested that the reinforcement learning process, characterised by increased variability, may persist even during the chronic stage of LBP and that the differences in spinal movement variability could be more related to the levels of pain intensity and disability rather than the chronicity of the symptoms.

Previous research has established an association between pain-related threat beliefs and disability factors and trunk kinematics in LBP, however, limited number of studies have investigated the impact of those factors like fear of movement on trunk kinematic variability (Shanbehzadeh et al., 2022). In *Chapter Two*, only one of the reviewed studies investigated the correlation between pain-related fear and trunk movement variability in people with chronic LBP (Fujii et al., 2022). Therefore, further investigations were taken to explore the relationship between movement variability and pain-related psychological factors in *Chapter Three* and *Chapter Six*.

Chapter Three revealed a linear correlation between lumbar kinematic variability and fear of movement, which indicates reduced ability of people with CNSLBP with higher fear of movement to predict the parameters needed to perform the underlying motor task which subsequently resulted in increased movement variability (Schmidt, 2003). However, this study did not find any association between spinal kinematic variability and pain intensity nor disability.

In contrast, *Chapter Six* identified inverse relationships between spinal kinematic variability, revealed by parameters of the HA, and the extent of LBP intensity, disability, and fear of movement. In addition to the observed increase in spinal kinematic variability in people with CNSLBP during repetitive trunk movements compared to asymptomatic individuals, those with higher levels of pain, disability, and fear of movement exhibited the lowest spinal kinematic variability. This supports the concept of ‘’tight control’’ over trunk movement, leading to more rigid trunk movements (Karayannis et al., 2013, van Dieën et al., 2019a, van Dieën et al., 2019b). These inconsistent findings between studies in *Chapter Three* and *Chapter Six*, could be attributed to the differences in the methods used to calculate spinal kinematic variability in each study. Unfortunately, this relationship could not be explored in *Chapter Four* due to the small sample size, however, those recruited with CNSLBP presented with significantly higher degrees of disability, and fear of movement compared to asymptomatic individuals.

7.4 Quality of evidence for the conclusions of this thesis

The quality of research conducted in this thesis has been evaluated using a range of risk of bias assessment tools and reporting guidelines to ensure that meaningful conclusions can be drawn. In *Chapter Two*, the systematic review was assessed according to the guidelines for A Measurement Tool to Assess Systematic Reviews 2 (AMSTAR-2), a tool designed to assess the quality of

systematic reviews (Shea et al., 2017). When applying the assessment tool to evaluate the systematic review, it is evident that most items in the checklist were met, including that the research question and inclusion criteria for the review included the component of PICO, the use of a comprehensive literature search strategy using several databases, providing a list of excluded studies with justifications, and including two independent reviewers for study selection and data extraction (Shea et al., 2017). One component that was not met is reporting the sources of funding for the studies included in the review. The main reason for this was that not all the included studies mentioned their funding sources. Yet, in cases where funding was mentioned, it was stated that it didn't affect how the study was conducted or reported. Which emphasises the importance of clear reporting of funding information to allow for a comprehensive evaluation of potential biases or conflicts of interest.

The protocol of this systematic review was published in advance, registered on PROSPERO and the review was conducted according to PRISMA guidelines (Moher et al., 2015). The methodological quality of the included studies was assessed to evaluate the risk of bias in each study using a modified version of D&B scale (Downs and Black, 1998, Mazaheri et al., 2021). Moreover, the quality of evidence was assessed using the GRADE approach (Atkins et al., 2004). The overall quality of evidence was downgraded from low to very low. This was primarily due to inclusion criteria that limited the review to observational studies. Additionally, the use of heterogeneous metrics for analysis and varying effect sizes contributed to the downgrade of evidence to a very low level. However, all included studies were rated as high to medium methodological quality, with no study rated as low quality based on the D&B scale. Therefore, these factors collectively ensure no bias has been introduced into this review. To maintain a consistent standard of quality in this thesis, the same modified D&B scale was applied for assessing the risk of bias of the studies in *Chapter Three*, *Chapter Four*, and *Chapter Six*. However, *Chapter Five* was

exempt from this assessment due to its unique nature as a single-group study involving only asymptomatic individuals. All three studies were rated as high quality based on the modified D&B scale, with a low risk of bias. However, it is important to acknowledge that these assessments were conducted by the author of the studies, which introduces a potential source of bias in the evaluation process. Incorporating these three studies into the systematic review reported in *Chapter Two,* and using the GRADE approach to assess the overall quality of evidence, did not change the review's conclusion. The overall quality of evidence remains very low, primarily due to the observational nature of the included studies and the heterogeneity in metrics used for analysis.

All studies conducted in this thesis and reported in *Chapter Three*, *Chapter Four*, *Chapter Five*, and *Chapter Six*, were conducted according to the Declaration of Helsinki to ensure ethical treatment of participants (Riis, 2003). Although it does not address bias directly, it indirectly contributes to bias reduction for example by ensuring participants comprehensive understanding of the study objective, procedures, and potential risks through informed consent. In addition, all the empirical studies reported in this thesis followed the STROBE guidelines (von Elm et al., 2008). Moreover, the STROBE guidelines do not specifically evaluate bias, however, it provides a framework to assess the study, and ensure transparency in reporting of results. Nevertheless, all potential measures have been implemented to limit bias in reporting the results of this thesis.

7.5 Overall strengths, limitations and implications for clinical and future research

In order to evaluate spinal kinematic variability, several challenges were encountered while conducting the research presented within this thesis. As outlined in *Chapter One,* optoelectronic motion capture systems are the gold standard in motion capture. However, the use of these systems

introduce soft tissue artefact due to the movement of the markers on the skin which impact the estimation of spine kinematics that is one of the most significant source of error in the analysis of human movement (Leardini et al., 2005). Nevertheless, there is no standardised approach on how to measure spine motion, primarily due to methodological differences involved when assessing kinematics such as the number of reflective markers, the set of the markers or their location on the spine (Mason et al., 2016).

In *Chapter Three*, *Chapter Four*, *Chapter Five*, and *Chapter Six,* a 3D motion capture system was used to record the experiments in order to measure spine kinematics using customised models for segmenting spinal motion. Despite its effectiveness, is not typically utilised in clinical settings due to the technical difficulties and the time in implementing such a method, in addition to the challenges and limitations associated with these systems. In contrast, wearable sensor technology is advancing rapidly, enabling tracking of human motion using smaller and lighter devices that have greater data storage capabilities (Lang et al., 2020). Moreover, the establishment of standardised protocols and guidelines to integrate these systems into clinical practice would facilitate recoding segmental spinal motion and maximise the benefits of this valuable technology within clinical settings and for future research.

Chapter Two highlighted the importance of standardising terminology and considering conceptual differences when using different metrics of variability in the assessment of spinal kinematic variability (Alsubaie et al., 2023a). Applying the same linear metric to measure spinal kinematic variability in *Chapter Three* and *Chapter Four* have yielded similar results with different conclusions based on the task performed in each experiment. In *Chapter Three* we used a novel approach to provide instantaneous feedback based on trunk kinematics that is unique to this study unlike the commonly used EMG biofeedback in research and clinical practice. However, the nature of the trunk movements performed was not functional enough to reflect a task of daily living. In

order to accomplish this, in *Chapter Four*, a more complex multi-planer lifting task was designed to fulfil this goal. Despite the relatively small sample size in this study, modest mean differences in spine kinematic variability of around three degrees was detected between people with CNSLBP and asymptomatic individuals, the effect sizes ranged from moderate to large. Nevertheless, it is still unclear whether this observation had meaningful clinical implications. Thus, further studies with larger sample sizes are recommended to improve generalisability of the findings.

Chapter Five and *Chapter Six*, reported the first attempt to use the parameters of HA as a novel measure of spinal kinematic variability. The parameters demonstrated excellent reliability during active cervical rotation (Barbero et al., 2017). Yet, the validity and reliability of this measure have not been investigated previously for other spinal levels, which may differ especially in people with LBP. Furthermore, the pelvic movement in these studies during repetitive trunk movements was not constrained, however, any unnecessary pelvic motion was limited by performing the task in sitting position.

The primary aim of the thesis was to understand the behaviour of spinal kinematic variability in individuals with CNSLBP compared to asymptomatic individuals, and to identify a suitable method of analysis that combines the advantages of both linear and nonlinear metrics. Although the systematic review in *Chapter Two* explored the differences between metrics, direct comparisons between them were not conducted within the scope of this thesis. Therefore, future research comparing the meanSD and HA parameters in analysing spinal kinematic variability would provide deeper insights into the conceptual differences associated with utilising different metrics of variability.

In this thesis, the co-contraction measures were mainly utilised to assess trunk muscle activity. However, it is important to recognise the associated limitations, particularly concerning the diverse

normalisation procedures employed. Accurate normalisation is crucial for the meaningful understanding of co-contraction data, yet it poses challenges and potential shortcomings. Normalisation techniques vary widely across studies, with the most common method being the use of maximum voluntary contraction (MVC). However, obtaining normalisation values via MVC poses difficulties in individuals experiencing pain, introducing potential bias and hindering interpretation. Therefore, in this thesis, MVC normalisation was not used. Instead, adapted methods were utilised in *Chapters Three, Five,* and *Six*. While the adapted methods, especially the one outlined in *Chapter Three,* is deemed acceptable, it is essential to recognise that the possibility of bias persists, particularly in individuals with CNSLBP, who may exhibit differing resting EMG amplitude levels before movement initiation compared to those without CNSLBP.

The research conducted in this thesis involved a thorough examination of both trunk kinematics as well as trunk muscle EMG activity, however, kinetic data, such as ground reaction forces, was not recorded in any of the empirical studies. This aspect could be considered for investigation in future research as it may serve as a potential contributing factor to the variability observed in spinal movement.

Participants with CNSLBP recruited in studies of *Chapter Three*, *Chapter Four* and *Chapter Six,* presented with mild current pain intensity (1.9 ± 2.1, 2.82 ±2.04, and 3.26±1.69, on a scale of 10, respectively) and minimal disability level on the ODI at the time of testing (10.8 ± 6.7, 15.59 ± 7.82, and 16.05±8.5, respectively). Furthermore, participants with CNSLBP recruited in studies of *Chapter Three*, *Chapter Four* and *Chapter Six,* presented with following levels of fear of movement on FABQ- work scale (9.1 ± 8, NR, and 9.52±7.22, respectively), FABQ- physical scale (13.5 ± 4.4, NR, and 10.47±4.53, respectively) and FABQ- total (NR, 26.73±11.55, and 25.00±11.19, respectively). The level of fear was not assessed in asymptomatic individuals except in one study in *Chapter Four,* where people with CNSLBP presented with significantly higher degrees of fear of

movement compared to asymptomatic individuals. Therefore, our findings may be applicable to individuals with similar clinical presentations, however, this warrants further investigation involving participants experiencing higher levels of chronic pain, disability and fear of movement.

As highlighted in *Chapter Two*, the direction of difference in spinal kinematic variability, whether less or more variable in people with CNSLBP compared to asymptomatic individuals, is still not established. However, given the evidence provided in this thesis and the new insights gained on motor adaptations to spinal pain, people with CNSLBP tend to increase their spinal movement variability during repetitive trunk motion. While this thesis primarily concentrated on movement variability, the findings challenge the existing paradigms by highlighting discrepancies between observed outcomes and theoretical predictions. This discrepancy may arise from the complex interplay of various factors influencing motor control and movement variability. As a result, this work suggests the possibility of a new working hypothesis emerging, which integrates aspects of both movement variability and stability to adaptively respond to diverse movement contexts. This potential hypothesis could provide a more comprehensive framework for understanding the adaptability of motor control in people with CNSLBP.

Different interventions may be required to address the unique presentation of each individual. Based on the insights gained from this thesis on movement patterns and motor control deficits, clinicians may conduct a thorough assessment to identify the behaviour of movement variability contributing to the patient's symptoms. This could then be used to develop a tailored interventions by applying strategies to enhance trunk motor control through targeted exercises to improve function of deep trunk muscles (van Dieën et al., 2019a, van Dieën et al., 2019b). A recent randomised control study showed that neuromuscular exercises designed to enhance strength, balance, endurance, and coordination have yielded a positive treatment effect on lumbar movement variability and persisted even six months after the intervention, indicating sustained and longer-term

improvement (Bauer et al., 2019). Moreover, depending on the presented movement variability behaviour, whether it involves an increase or decrease in kinematic variability, clinical practitioners should consider variability as an element of real-world contexts (Lindsay et al., 2023). Tailored interventions might involve simulating a target level of variability through biofeedback training, ensuring spine health and minimising the risk of injury. Biofeedback training demonstrated effectiveness to facilitate learning and prepare individuals to successfully engage in physical training by reducing fear of movement, ultimately resulting in reduction in pain and limitations of activity (Kent et al., 2015, Verhoeff et al., 2009). This approach may be integrated during the early stages of training in order to teach people with LBP how to perform the exercises correctly by controlling their lumbar neutral zone.

7.6 Conclusion

This thesis provides evidence indicating that individuals with CNSLBP when compared with asymptomatic individuals exhibit different motor behaviour when performing repetitive trunk movements. The research in this thesis revealed how people with CNSLBP tend to execute trunk movements at a slower pace with increased spinal kinematic variability across multiple repetitions of a task. It is notable that they may exhibit a comparable range of spinal motion as asymptomatic individuals, however, they adjust their movement pattern by modifying movement variability, potentially in an effort to find a more suitable motion path that alleviates pain and minimises spine strain and fatigue during repetitive trunk movements. Additionally, this thesis supports the concept that people with CNSLBP display the same extent of trunk muscle co-activation as asymptomatic individuals, however, there is a relationship between the level of this activation and spinal kinematic variability. Moreover, an association was found between fear of movement and

movement variability, as people with CNSLBP may adjust their movement patterns in response to their level of fear.

Overall, this thesis highlights an interaction between physical and psychological features of people with CNSLBP. Finally, it offers new insights into how motor adaptations to spinal pain manifest in movement behaviour, indicating the need for personalised interventions to address the unique presentation of each individual with CNSLBP.

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APPENDICES

Appendix 1 - Alsubaie et al. (2021a)

Appendix 2 - Alsubaie et al. (2023a)

Appendix 3 - PRISMA Checklist for *Chapter Two*

Appendix 4 - Alsubaie et al. (2021b)

Appendix 5 - Ethical Review, Consent form and Patient Information Sheets for *Chapter Three*

Appendix 6 - Alsubaie et al. (2023b)

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Appendix 8 - Ethical Review, Ethical Amendments, Consent Forms, Patient Information Sheets and Recruitment posters for *Chapters Five and Six*

Appendix 1 - Alsubaie et al. (2021a)

BMJ Open

Is movement variability altered in people with chronic non-specific low back pain: a protocol for a systematic review

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ABSTRACT

Introduction Motor variability is an important feature when performing repetitive movement, and in asymptomatic people functional tasks are typically performed with variable motor patterns. However, in the presence of chronic non-specific low back pain (LBP), people often present with different motor control strategies than those without pain. Movement variability has been assessed using a wide range of variables, including kinetic and kinematic components of motion. This has resulted in a wide range of findings reported in the literature and some contradicting results. Therefore, the aim of this systematic review is to investigate whether the amount and structure of motor variability are altered in people with chronic non-specific LBP, during both repetitive non-functional and functional tasks.

Methods and analysis This protocol for a systematic review is informed by Cochrane guidelines and reported in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis Protocols. MEDLINE, EMBASE, CINAHL, ZETOC, Web of Science, PubMed and Scopus will be searched from their inception to December 2020 along with a comprehensive search of grey literature and key journals. Two independent reviewers will conduct the search, extract the data, assess risk of bias (using the Downs and Black Scale) for the included studies and assess overall quality of evidence based on Grading of Recommendations, Assessment, Development and Evaluation guidelines. Meta-analysis will be conducted if deemed appropriate. Alternatively, a narrative synthesis will be conducted and evidence summarised as an increase, decrease or no change in the motor variability of people with LBP compared with healthy controls.

Ethics and dissemination This study raises no ethical issues. Results will be submitted for publication in a peer review journal and presented at conferences.

PROSPERO registration number CRD42020211580.

Strengths and limitations of this study

- This systematic review will be the first to rigorously summarise and evaluate the current body of evidence assessing motor variability in people with chronic non-specific low back pain.
- The protocol is written in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocols guidelines.
- The methodology of this protocol allows for a wide range of tasks to be considered, including functional and non-functional tasks.
- Based on the methodological diversity among possible eligible studies, a meta-analysis may not be possible.
- The qualitative method used to synthesise the evidence provides the direction of the effect for individual studies without considering the overall magnitude or precision of the effect size.

INTRODUCTION

The socioeconomic burden of low back pain (LBP) is increasing rapidly despite advances in diagnosis and management. In approximately 85%–90% of cases, the pathoanatomical cause of LBP cannot be identified, hence the term non-specific LBP.[1 2] One of the main reasons for individuals with LBP to seek care is limitation of their functional ability[3] which may include reduced physical performance (e.g., strength, mobility, balance, endurance, and coordination).[4]

Repetitive movements during work or activities of daily living can result in injury, especially of the low back.[5] Variation in movements, posture or muscle activity has been suggested as an effective strategy to minimise the load associated with repetitive movements and hence may prevent or delay any potential musculoskeletal injury.[6] Motor variability is an important feature to consider when performing repetitive movement, and in asymptomatic people functional tasks are typically performed with variable motor patterns.[7] The biological systems illustrate an inherited normal variation (lying between too much variability and complete repeatability) in both space and time to maintain or achieve functional skills.[8] However, in the presence of LBP, people often present with

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different motor control strategies than those without pain,[9] and changes in motor variability are often reported in both kinematic parameters (e.g., reduced trunk–pelvis coordination and the degrees of freedom during walking or other activities of daily living)[10 11] and neuromuscular variables (e.g., reduced variability of muscle activity during repetitive lifting or other fatiguing tasks).[6 12]

Using different methods to measure human movement, variability has been assessed at various levels, including kinetic and kinematic components of motion, coordinative aspects of movement, and muscle activity and patterns of muscle recruitment.[13] Recently, with the emergence of a range of different mathematical approaches, researchers have used linear and non-linear tools to analyse the amount and structure of motor variability, respectively.[8 14 15] Linear tools to measure variability in terms of the statistical variance (e.g., range, standard deviation and coefficient variation) provide information only about the quantity of the movement but give no insight regarding the temporal variations of movement.[8] Therefore, non-linear tools are used to reveal the structure of variability or the time-evolving nature of the variations and hence provide additional information about the level of complexity of the motor system.[15 16] Non-linear measures employ a wide range of mathematical tools to capture the structure of variability, such as largest Lyapunov exponent,[16] uncontrolled manifold method or the noise-tolerance-covariance decomposition,[14] entropy measures, recurrence quantification analysis, discrete data analysis, normalised root mean square, Cauchy criterion and cluster analysis.[15]

The various methods used to measure variability in people with LBP have resulted in a wide range of results with some contradicting findings. For example, some studies report increased movement variability during gait in people with LBP.[17 18] Other studies report reduced variability during functional or non-functional tasks, which supports the argument that people with LBP increase trunk stiffness as a protective response to pain.[19 20] Other studies have shown no significant difference or change in motor variability in people with LBP.[21 22] The inconsistency in the literature regarding the influence of LBP on motor variability highlights the need to systematically review and synthesise the current literature. To date, there is no comprehensive systematic review that assesses motor variability in people with chronic non-specific LBP. There are reviews that examined motor control changes in general, however, in this case, only specific functional tasks such as gait or standing were considered,[23 24] or the focus was on an older population only.[25]

Therefore, the aim of this systematic review is to investigate whether the amount and structure of motor variability measured in the thoracolumbar and lumbopelvic regions are altered in people with chronic non-specific LBP. Multiple outcome measures are considered, including kinetic, kinematic, coordination and spatiotemporal parameters, during both repetitive non-functional and functional tasks.

Table 1 Summary of inclusion and exclusion criteria

Inclusion criteria	
Population	Adults (≥18 years old), men and women with chronic non-specific LBP and healthy controls
Indicator/ exposure	Motion analysis systems (eg, optoelectronic systems, inertial measurement unit sensors)
Comparison	Difference between people with chronic non-specific LBP and healthy controls
Outcomes	Amount and/or structure of movement variability based on linear or non-linear measures
Study type	Quantitative cross-sectional observational studies
Exclusion criteria	
Population	Individuals under the age of 18, people with LBP attributable to a specific pathology, concurrent systemic disorders, surgery, cardiovascular conditions or pregnancy
Indicator/ exposure	None
Comparison	None
Outcomes	Studies used spatiotemporal parameters based on neuromuscular variables
Study type	Cadaveric or animal studies, single-subject case reports and longitudinal cohort studies. Studies not written in English will be excluded

LBP, low back pain.

METHODS

The protocol for this review was developed in accordance with the updated guidelines of the Cochrane Back and Neck Group, Cochrane Handbook for Systematic Reviews of Interventions and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocols (PRISMA-P)[26–28] (online supplemental file 1). This protocol was registered on PROSPERO on 10 December 2020.

Eligibility criteria

The inclusion and exclusion criteria of the studies to be included in the review are detailed using the PICOS (P: Population; I: Indicator/Intervention; C: Comparator; O: Outcome(s); S: Study design) framework[28 29] (table 1).

Population

Studies that investigated adults aged 18 years or older with chronic non-specific LBP that persisted for at least 3 months with no diagnosable underlying pathology will be considered for inclusion.[30] For the purpose of this review, adults without a history of LBP will represent the control group. Studies will be excluded if they recruited people with LBP due to trauma, fractures, spinal stenosis or radicular pain. Studies will be eligible that included people

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Table 2 Summary of outcome measures

Outcome measures domains			
Concept measured	Broad domains	Narrow domains	
Movement variability, captured using movement outcomes specifically related to thoracolumbar and lumbopelvic segments during both functional and non-functional tasks	Amount or magnitude of variability—for example, using traditional linear measures (statistical variance)	SD	
		Range	
		Coefficient of variation	
	Structure and nature of variability—for example, using non-linear dynamics	Intra-trial	Entropy measure
			Recurrence quantification analysis
			Largest Lyapunov exponent
		Inter-trial Inter-subject	Normalised root mean square
			Cauchy criterion
			Cluster analysis
			Uncontrolled manifold

with LBP and healthy participants with no concurrent systemic disorders, including rheumatic and neuromuscular disorders, spinal deformity or surgery, cardiovascular conditions and pregnancy.

Indicator

Studies will be included if they used any method to quantify spinal movement at the thoracolumbar and lumbopelvic level in the form of kinetic, kinematic, coordination or spatiotemporal parameters using motion analysis systems (eg, optoelectronic systems, inertial measurement unit sensors).[19 31]

Comparison

Included studies should have compared motor variability between individuals with chronic non-specific LBP and healthy controls while preforming functional (eg, gait) or non-functional tasks (eg, repetitive trunk movements).

Outcomes

Studies that used any outcome to quantify motor variability will be considered. The outcomes include the amount of motor variability captured by linear tools or the structure of motor variability recorded by non-linear tools.[8] The wide range of movement variables may use kinetic or kinematic components of motion, coordinative aspects of movement or spatiotemporal parameters (table 2).

Study design

Observational cross-sectional studies will be reviewed, excluding cadaveric or animal studies and single-subject case reports as well as studies not written in English.

Information sources

The following databases will be searched from their inception to December 2020: MEDLINE (OVID Interface), EMBASE (OVID Interface), CINAHL (EBSCO Interface), ZETOC (EBSCO Interface), Web of Science, PubMed and Scopus. In addition to the database searching, hand-searching of key journals will be conducted. This will include the following key journals: *Journal of Electromyography and Kinesiology*, *Clinical Biomechanics*, *Journal of Biomechanics*, *Human Movement Science*, *The Clinical Journal of Pain*, *Spine*, *Journal of Orthopaedic & Sports Physical Therapy*, *Musculoskeletal Science and Practice* and *Journal of Back & Musculoskeletal Rehabilitation*.

Distinguished authors in the field will be contacted to identify any relevant work which is currently in preparation or unpublished to carry as extensive search as possible to reduce the risk of publication bias and to identify as much relevant evidence as possible. Grey literature will be included in the search using the British National Bibliography for Report Literature, OpenGrey database, ProQuest Dissertations & Theses Global, and EThOs. Key congresses and meetings in the field will be assessed from 2017 to 2020, including the World Congress of Biomechanics and the International Society of Electrophysiology and Kinesiology congresses. In accordance with the Methodological Expectations of Cochrane Intervention Reviews standards, hand-searching will be conducted to check reference lists in included studies and any relevant systematic reviews identified.[32]

Search strategy

A comprehensive, systematic and reproducible search strategy will be completed by the lead author (AMA). The search strategy has been developed using medical subject heading (MeSH) (including exploded terms) combined with keywords to ensure maximal retrieval. The search strategy will be developed in accordance with the defined PICOS components and will be linked with the Boolean terms AND/OR where relevant. There will be no restrictions implemented during the search in terms of the study design, region or date. The search strategy will remain consistent between databases. However, appropriate modifications with relevant syntax and MeSH terms will be performed to the main search strategy to adapt for other databases. A draft-developed search strategy for MEDLINE (OVID interface) database is available in online supplemental file 2.

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Data management

Search data will be imported into EndNote V.X9 (Clarivate Analytics), including citations, abstracts and full text of relevant studies. One reviewer (AMA) will upload studies, identify any duplicate results and remove these prior to the screening process. A complete list of all potentially eligible studies with full text will be stored in EndNote V.X9 and is ready for screening process by two independent reviewers (AMA and MM).

Selection process

An electronic screening form will be created and piloted based on the eligibility criteria to subcategorise the studies into include/exclude/unclear. In the initial step of the screening process, AMA and MM will assess and subcategorise studies based on the title and abstract using the developed screening form. In the case that the eligibility is unclear from the title and abstract, the reviewers will read the full text of the article to assess inclusion. If it is still unclear, reviewers will discuss article eligibility. In the event of disagreement, a third reviewer (DF) will be asked to mediate the process. The study selection process will be summarised and depicted using the PRISMA flow diagram.[27] During all assessment stages, agreement between reviewers will be estimated with percentage of agreement and the κ statistic using SPSS for Windows statistical software package (IBM SPSS Statistics V.25).

Data collection process

Using a standardised form developed to extract data, both reviewers (AMA and MM) will independently extract information from eligible studies. Any disagreement between reviewers will be mediated through discussion with a third reviewer (DF) if needed. Prior to data collection, the data extraction form will be piloted to ensure all relevant information is collected, and any necessary changes will be implemented prior to data extraction from all eligible studies.

Data items

The characteristics of the included studies are summarised and presented in table 3. In the case of missing data or if the results are presented in an ambiguous way, the corresponding author will be contacted for clarification. If the author does not respond within a set time frame (up to 6 weeks) or the provided clarification affects the eligibility, the study will not be considered for review. If two or more papers appeared to use the same sample, the authors will be contacted for further information to ensure data are not duplicated in the review.

Risk of bias

Unlike the abundance of instruments developed to judge the methodological quality of randomised clinical trials, there is lack of a gold-standard instrument designed for quantifying the quality of observational cross-sectional studies. Hence, a modified version of Downs and Black Scale,[35] designed for assessing the quality of both randomised and non-randomised studies, will be used for quality rating in this study. The modified version consists of four domains (12 items), including quality of reporting (7 items), the generalisability of results or external validity (1 item), the relationship between LBP and outcomes, known as internal validity (4 items) and the adequacy of sample size or study power (1 item) (table 4). Two authors (AMA and MM) will separately assess the quality of the eligible studies.

Table 3 Characteristics of included studies

Information area	Data extracted
General study information	Authors Year of publication Title Study design
Patient characteristics	Age, sex, anthropomorphic data, sample size (healthy and LBP) LBP details (pain duration, current and past pain intensity, pain location)
Methodology	Setting Details of task preformed (functional or non-functional, length of recording, repetition, position, etc) Instrument used (3D capture system, Inertial measurement unit sensor etc) Regions of the spine assessed (eg, thoracolumbar or lumbopelvic)
Outcome	Amount or structure of motor variability using any movement outcome related to kinetic, kinematic and coordinative aspects of movement or spatiotemporal parameters of movement

3D, three-dimensional; LBP, low back pain.

Data synthesis

Based on the methodological diversity revealed among the possible eligible studies during the scoping search, pooling of data may not be possible; however, this will not be ruled out and meta-analysis will be conducted if possible. If a meta-analysis is deemed not possible, a narrative synthesis will be performed. An initial step of our synthesis is to systematically and comprehensively assess the results of each study—highlight any important characteristics of the studies, especially the important similarities or differences. Ideally, the processes of narrative synthesis should avoid bias by following a clear specified method in advance. We will make further decisions at review stage about how best to organise and present the data based on the actual review findings.[31]

Results of the included studies will be organised in subgroups in the same order as the comparisons and outcomes. To improve consistency, the following items will be contained[26]: overall quality of evidence, the number of participants, the outcome measures, results

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Table 4 Quality rating instrument adjusted specifically for the current review (informed by Downs and Black Scale)

Item	Scoring guideline
Reporting	
1. Is the hypothesis/aim/ objective of the study clearly described?	
2. Are the main outcomes to be measured clearly described in the introduction or Methods section?	
3. Are the inclusion/exclusion of the participants included in the study clearly described?	
4. Are the demographic characteristics of the participants included in the study clearly described?	The question is answered 'yes' if information about *age and gender* is provided
5. Are the clinical characteristics of the participants included in the study clearly described?	The question is answered 'yes' if information about *LBP type, duration, severity* or *disability level* is provided
6. Is the treatment history of the LBP participants clearly described?	
7. Does the study provide estimates of the random variability in the data for the main outcomes?	The question is answered 'yes' if studies have provided quantitative values of the SE, SD or CI (for normally distributed data) and IQR (for non-normally distributed data)
External validity	
8. Were the participants who were asked to participate in the study representative of the entire population from which they were recruited?	The question is answered 'yes' if the studies have used several recruitment methods (eg, self-report, hospital, insurance companies)
Internal validity/bias and confounding	
9. If any of the results of the study were based on 'data dredging', was this made clear?	The question is answered 'yes' if no retrospective unplanned subgroup analyses were reported
10. Was an attempt made to blind those measuring the main outcomes?	
11. Were the main outcome measures representing movement variability reliable?	The question is answered 'yes' if there is a reference to a reliability study or information on these features in the paper and this paper should cover the field of interest (LBP)
12. Were controls matched with LBP participants in important characteristics?	The question is answered 'yes' if appropriate matching on confounders, that is, age and gender, was performed or if adjustment for these variables is made in the statistical analysis
Power	
13. Was there an appropriate sample size of LBP participants and controls?	The question is answered 'yes' if a sample size justification or power description is provided

LBP, low back pain.

of quantitative analyses (effect size/ Confidence interval CI) and results of qualitative analyses (direction of the effect; an increase, decrease or no change in the motor variability of people with LBP compared with healthy controls).

Examining the effects of heterogeneity will also be assessed, especially how the results of the included studies might be affected by factors such as methodological differences between studies.[34] The robustness of the results will be assessed with a sensitivity analysis to test the effect of quality/risk of bias on the results by excluding studies that were characterised as high risk of bias.[35]

Confidence in cumulative estimate

The Grading of Recommendations Assessment, Development and Evaluation (GRADE) method will be used to rate the overall cumulative quality of the evidence across individual studies.[36] The pooled data will be assessed based on five determinants of the GRADE: risk of bias[37]; inconsistency, heterogeneity in studies in the review (eg, age group and severity of spinal pain)[38]; indirectness; imprecision (larger sample sizes indicate greater precision)[39]; and, finally, publication bias arising from non-publication of relevant results.[40]

As it is anticipated that the included studies will be mostly observational studies with cross-sectional designs, these studies will be given a 'LOW' rating initially in the GRADE framework. However, from this point, the quality of evidence of the study can then be downgraded or upgraded depending on the above determinants. It can also be upgraded based on the large effect sizes or a large number of studies indicating the same direction of effect. Following this process subsequently, quality of evidence will be graded as 'VERY LOW', 'LOW', 'MODERATE' or 'HIGH' according to the GRADE guidelines.[41]

Patient and public involvement

The research question in this study forms part of a larger discussion within our patient and public involvement meetings. Patients will not be involved in the analysis and data collection of the systematic review.

Clinical implications of this study

Motor variability is considered as an important feature of motor control and is therefore relevant to measure and consider in assessment and management of people with LBP.[8] However, it is not well established to what extent motor variability can be affected in the presence of chronic LBP. Thus, the results of this systematic review may identify various features of motor variability which are altered in people with chronic LBP, and subsequently influence the direction of clinical practice.

ETHICS AND DISSEMINATION

No ethical approval is required for this review as the data that will be used in this systematic review will be collected from previously published studies. The results of this

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systematic review will be submitted for publication in a peer review journal and presented at conferences.

Amendment protocol

Where amendments are required from the protocol during the review process, these amendments will be documented on PROSPERO. All amendments will be clearly marked with the date of the amendment and a description of the changes, alongside a justification for the change.

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Contributors All authors contributed to the focus of the systematic review topic. AMA is a PhD student with DF as lead supervisor and EM-V as co-supervisor. AMA is the first reviewer for this systematic review, and MM is the second reviewer. AMA drafted the initial protocol with guidance and feedback at all stages from DF, EM-V and MM. All authors have revised and reviewed each draft of the protocol and have approved the final manuscript. DF is the guarantor.

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Appendix 2 - Alsubaie et al. (2023a)

PLOS ONE

RESEARCH ARTICLE

Is movement variability altered in people with chronic non-specific low back pain? A systematic review

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Abstract

Background

Variability in spine kinematics is a common motor adaptation to pain, which has been measured in various ways. However, it remains unclear whether low back pain (LBP) is typically characterised by increased, decreased or unchanged kinematic variability. Therefore, the aim of this review was to synthesise the evidence on whether the amount and structure of spine kinematic variability is altered in people with chronic non-specific LBP (CNSLBP).

Methods

Electronic databases, grey literature, and key journals were searched from inception up to August 2022, following a published and registered protocol. Eligible studies must investigated kinematic variability in CNSLBP people (adults ≥18 years) while preforming repetitive functional tasks. Two reviewers conducted screening, data extraction, and quality assessment independently. Data synthesis was conducted per task type and individual results were presented quantitatively to provide a narrative synthesis. The overall strength of evidence was rated using the Grading of Recommendations, Assessment, Development and Evaluation guidelines.

Findings

Fourteen observational studies were included in this review. To facilitate the interpretation of the results, the included studies were grouped into four categories according to the task preformed (i.e., repeated flexion and extension, lifting, gait, and sit to stand to sit task). The overall quality of evidence was rated as a very low, primarily due to the inclusion criteria that limited the review to observational studies. In addition, the use of heterogeneous metrics for analysis and varying effect sizes contributed to the downgrade of evidence to a very low level.

Interpretation

Individuals with chronic non-specific LBP exhibited altered motor adaptability, as evidenced by differences in kinematic movement variability during the performance of various repetitive functional tasks. However, the direction of the changes in movement variability was not consistent across studies.

Introduction

Low back pain (LBP) affects the majority of the worldwide population at some point during their lifetime [1, 2]. Understandably, LBP can have a substantial effect on the quality of life of those affected [3, 4].

People with LBP move differently than pain free individuals [5, 6]. However, the underlying mechanisms of motor adaptations to pain still require further clarification at both the micro (e.g. single motor neuron) and macro (e.g. whole muscle behaviour) levels [6]. One common motor adaptation to pain is changes in spine kinematics, such as angular displacement, angular velocity, smoothness, and variability of movement [6–8]. Variability of movement is a common feature of human movement, especially during routine daily activities requiring repetitive (cyclic) movements [9, 10]. As an example, one study showed that people with LBP show more variability in coordination between the spine and pelvis during sit-to-stand, which is likely a strategy to find an optimal pain-free pattern [11].

Several theories have been proposed to describe natural variability in motor performance [12–14]. Some theories propose that decreased variability generally indicates a highly stable and coordinated behaviour [10]. Increased variability could also be considered as a beneficial component for motor performance, as it may reduce the risk of injury by distributing joint loads [15]. However, it is not well established how trunk movements should ideally be performed in terms of the adequate amount of motor variability, stability and complexity to achieve a coordinated movement that doesn't predispose an individual to injury, specifically during dynamic and repetitive tasks [16].

Changes in motor variability in people with LBP has been assessed in various ways, including assessing the variability of kinetic and kinematic measures, 'coordinative' aspects of a movement pattern, as well as muscle activity patterns [17]. However, it remains unclear whether movement in people with LBP is typically characterised by increased, decreased, or unchanged variability [18–21]. One possible reason for this is the large variation seen across individuals with LBP [22]. Another possible reason is the use of various linear and non-linear measurement tools to quantify the amount and structure of motor variability, respectively [23–25]. Both the amount and structure of variability functionally represent different aspects of motor performance and can vary independently from one another [23].

Systematic reviews have examined biomechanical and neuromuscular changes in people with LBP, and to a lesser extent, the motor variability during specific functional tasks, such as gait and quiet standing [26, 27], or balance performance for a specific age category, i.e. elderly [28]. However, only scoping reviews have examined motor variability in the presence of spinal pain [20, 21]. Both reviews revealed large heterogeneity between study designs and results. Dijk et al. 2021, attributed the inconsistent findings between studies to differences in normalization methods, changes in functional tasks, and differences in pain intensity or fear-avoidance behaviours of those with LBP [20]. Although Dijk et al. 2021 included participants with chronic LBP, motor variability was assessed based on electromyography (EMG) recorded

from the thoracolumbar region and kinematic movement patterns in all regions (e.g., including the knee) during functional tasks.

To date, no systematic review has synthesised findings on kinematic variability of the spine in people with chronic non-specific LBP during the performance of repetitive functional tasks. Therefore, the aim of this systematic review was to synthesise the evidence on whether the amount and structure of motor variability in kinematics (such as joints displacement, acceleration, and velocity) are altered in people with chronic non-specific LBP at the thoraco-lumbar and/or lumbo-pelvic regions.

Methods

This systematic review was planned according to the updated guidelines of the Cochrane Back and Neck Group [29], Cochrane Handbook for Systematic Reviews of Interventions [30], and the review is reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (S1 Table) [31]. The protocol was registered a priori with PROSPERO, Centre for Reviews and Dissemination, University of York, (CRD42020211580) on 10/12/2020, and the protocol was published in advance [32].

Eligibility criteria

Eligibility criteria were defined with the PICOS framework (P: Population; I: Indicator/ Exposure; C: Comparator; O: Outcome(s); S: Study design) [30, 33]. Eligibility criteria are summarized in (Table 1).

Population

The population of interest were men and women with an age of 18 years and above with chronic non-specific LBP that persisted for at least 3 months with no diagnosable underlying pathology [34]. They did not present with concurrent systemic disorders including rheumatic and neuromuscular disorders, spinal deformity or surgery, cardiovascular conditions and

Table 1. Summary of inclusion and exclusion criteria.

Inclusion criteria	
Population	Adults (≥18 years old), men and women with chronic non-specific LBP
Indicator/ Exposure	Motion analysis systems (e.g. optoelectronic systems, inertial measurement unit sensors, etc.)
Comparison	Healthy controls
Outcomes	Amount or structure of kinematic variability based on linear or non-linear measures
Study Type	Quantitative cross-sectional observational studies
Exclusion criteria	
Population	Individuals under the age of 18, people with LBP attributable to a specific pathology, concurrent systemic disorders, surgery, cardiovascular conditions or pregnancy
Indicator/ Exposure	None
Comparison	Individuals under the age of 18, concurrent systemic disorders, surgery, cardiovascular conditions or pregnancy
Outcomes	Studies using spatio-temporal parameters based on neuromuscular variables (i.e. EMG signals) only
Study Type	Cadaveric or animal studies, single-subject case reports, longitudinal cohort studies, interventional studies including both randomized and non-randomized clinical trials, reviews, meta-analysis and study protocols as well as studies not written in English.

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pregnancy. Studies that recruited people with LBP due to trauma, fractures, spinal stenosis, or radicular pain were excluded from this review.

Indicator

Studies were considered eligible if they used motion capture systems (e.g. optoelectronic systems, inertial measurement unit sensors, etc.) to quantify variability of spinal movement at the level of thoraco-lumbar and/or lumbo-pelvic regions [23, 35].

Comparison. For the purpose of this review, adults without a history of LBP represented the control group. No concurrent systemic disorders including rheumatic and neuromuscular disorders, spinal deformity or surgery, cardiovascular conditions and pregnancy were present in the participants.

Outcomes. The main outcome of interest was kinematic motor variability, either the amount or structure measured based on a wide range of movement variables during repetitive functional tasks. Multiple kinematic outcome measures that quantified spinal movement at thoraco-lumbar and/or lumbo-pelvic regions were considered for the variability measures (i.e., amount or structure) including joint displacement (or range of motion), acceleration, velocity, coordination (a measure between two kinematic variables).

Study design. Observational cross-sectional studies were included. The following study types were excluded: cadaveric or animal studies, single-case studies, longitudinal cohort studies, and interventional studies including both randomized and non-randomized clinical trials, reviews, meta-analysis and study protocols as well as studies not written in English.

Information sources and search strategy

The following databases were searched initially from inception to 14th December 2020 by one reviewer (AMA); updated up to 23rd August 2022 by the same reviewer (AMA): MEDLINE (OVID Interface), EMBASE (OVID Interface), CINAHL (EBSCO Interface), ZETOC (EBSCO Interface), Web of Science, PubMed and Scopus. Reference lists of included studies and relevant reviews were checked. Moreover, hand searching was conducted of relevant key journals including: Journal of Electromyography and Kinesiology, Clinical Biomechanics, Journal of Biomechanics, Human Movement Science, The Clinical Journal of Pain, Spine, Journal of Orthopaedic & Sports Physical Therapy, Musculoskeletal Science and Practice and Journal of Back & Musculoskeletal Rehabilitation.

The search strategy was developed based on the PICOS framework using medical subject headings (MESH) identified during the scoping search (Table 1). A complete search strategy example used in MEDLINE (OVID interface) was provided in the published protocol [32] (S1 File). Appropriate modifications with relevant syntax and MESH terms was performed to the main search strategy to adapt for other databases and ensure consistency. Grey literature was included in the search using the British National Bibliography for Report Literature (BNBRL), OpenGrey database, ProQuest Dissertations & Theses Global and EThOs to reduce the risk of publication bias. Key congresses and meetings in the field were searched from 2017 to 2022, including the World Congress of Biomechanics (WCB) and the International Society of Electrophysiology and Kinesiology (ISEK) congresses.

Study selection

Records were retrieved from databases and imported into EndNote V.X9 (Clarivate Analytics). After the removal of duplicates, eligible studies were selected by two reviewers (AMA, MM) who independently conducted title and abstract screening of all retrieved studies against the predetermined eligibility criteria and categorised articles into 'include', 'unsure' (e.g., needs

full text review) and 'exclude'. Eligible full-text studies were screened by one reviewer (AMA) and the selection decision was confirmed by the second reviewer (MM). Any disagreement between the reviewers in the study selection process was resolved by discussion.

Data extraction and data items

One reviewer (AMA) extracted the data from the eligible studies using a customised data extraction form and then the accuracy was confirmed by a second reviewer (MM). A third reviewer (DF) was available to mediate any disagreements. WebPlotDigitizer software was used to extract data from figures when text and tables were not sufficient to obtain the main outcome results. The following components were extracted: Population (inclusion/exclusion criteria, sample size and demographic, i.e., sex, age, height, weight, body mass index, and clinical characteristics, such as pain intensity and duration, disability level, fear, and other psychological factors; Indicator (type of task performed, measurement instrument, and spine region assessed); Outcome (variability measure/metrics); and Results (mean and SD of outcome measures and their statistical significance.

Risk of bias assessment

Due to the lack of a gold-standard instrument designed to quantify the quality of observational cross-sectional studies, the methodological quality of the included studies was assessed using a modified version of Downs and Black Scale (D&B), designed for assessing the quality of both randomized and non-randomized studies [36]. Among various tools available, D&B is the most commonly used tool to assess the methodological quality of observational studies [37]. This was done independently by two reviewers (AMA, MM). The modified version consists of 4 domains (12 items) including quality of reporting (7 items), the generalizability of results or external validity (1 item), the relationship between LBP and outcomes, known as internal validity (3 items) and the adequacy of sample size or study power (1 item). Items 4, 5, 6 and 11 were specifically implemented from a previous review to fit the study design of the current review [38]. The scoring was simplified to a choice of 0 ("no"/"unable to determine") or 1 point ("yes"). Therefore, the total scores range from 0 to 12 and higher scores indicate a better methodological quality of the study [39, 40]. However, for the purposes of this review, the total score was presented with a percentage score; moderate quality when 60–74% of the applicable criteria was met; >75% as high and <60% as low quality [41, 42].

Summary measures and data synthesis

Due to the heterogeneity of the studies (i.e., nature of the task, spine region, the used variability measure and metrics), meta-analysis was not possible and therefore a narrative synthesis was conducted. The studies were sub-grouped according to the nature of the task preformed during the assessment. In contrast to previous reviews [20, 21], visualization of quantitative data was considered important in this study and hence effect estimates and their confidence interval for each study was presented in a forest plot without producing the overall estimate of effect. Results were reported using mean and standard deviation (SD). When standard error (SE) was reported, SD was calculated using the formula: $SD = SE^{*}\sqrt{N}$; N: sample size [43]. When the LBP population was presented as subgroups (i.e. male/female, low disability/high disability, athletes/non-athletes, or different pain intensity levels 1–10), we followed the Cochrane guidelines handbook and used approporiate formulae for combining groups [43]. Differences between the LBP and control groups were summarised using the standardised mean difference (SMD) and 95% confidence intervals (95% CI). Forest plots were produced in RevMan software (v.5.4 Cochrane Collaboration) [44].

Quality of evidence

The quality of evidence was assessed for the main outcome domain per task type using the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) approach [45]. The level of evidence was then graded by each reviewer independently where ratings were made as per 'high', 'moderate', 'low' or 'very low' [46]. Initially, since only observational studies were included, low quality of evidence was assigned to the primary outcome domain per task type preformed [47]. Then, the quality of evidence was rated considering five factors (limitations, inconsistency, indirectness, imprecision, publication bias) [47]. The D&B individual score for each study was integrated into the GRADE approach to define the study limitations of evidence (for each outcome domain) [48]. Therefore, if the evidence was mainly obtained from studies with low methodological quality (D&B score <60%), limitations were described as serious. No limitation was reported with moderate methodological quality studies (D&B range from 60 to 74%). Finally, the level of quality of evidence was upgraded when most of the findings came from studies with high methodological quality [48]. Overall, the level of evidence was identified as 'High', 'Moderate', 'Low', or 'Very Low' [47].

Results

Study selection

The database search retrieved a total 6949 records that were identified through both database and hand searching. After the removal of duplicates, 4775 records were title and abstract screened by the two reviewers. A total of 59 studies were retained for full text screening. Finally, 14 studies were obtained for quantitative narrative synthesis. The search strategy and reasons for exclusion (S2 File) are provided in the PRISMA flow chart in Fig 1.

Characteristics of included studies

All of the 14 included studies were observational studies published between 2001 and 2022 [19, 49–61]. In total, 380 people with chronic non-specific LBP were included (women: 41%; men: 55% except one study that did not mention the women/men ratio [59]) and 276 healthy people. The mean age of LBP participants ranged from 20.8 to 44.1 years with average pain intensity of 3.1 out of 10 on a numerical pain scale and an average pain duration of 34.7 months. The average disability level was 17.5% in studies that used Oswestry-disability-index (ODI) and 5.3 in studies that used Roland–Morris Disability Questionnaire (RDQ), indicating a minimal level of disability. Only three studies [19, 55, 57] assessed the fear-avoidance behaviour and beliefs using Tampa Scale for Kinesiophobia (TSK), with an average score of 30.9 indicating moderate levels of fear and avoidance [62], and only two [19, 55] measured catastrophic thinking related to pain using the Pain Catastrophizing Scale (PCS), with an average score of 11.25.

To facilitate the interpretation of the results, the included studies were grouped into four categories based on the task preformed. Detailed descriptions of the inclusion/exclusion criteria (S2 Table), and demographic and clinical characteristics of the included studies are presented in Table 2.

Narrative synthesis of results

The main findings of each study are summarised in Table 3 with more detailed description of the task preformed provided in S3 Table. The outcome measures of interest used in the eligible studies were drawn from either linear or non-linear metrics or both. The studies exhibited a significant degree of heterogeneity with respect to the spinal regions examined, the type of the

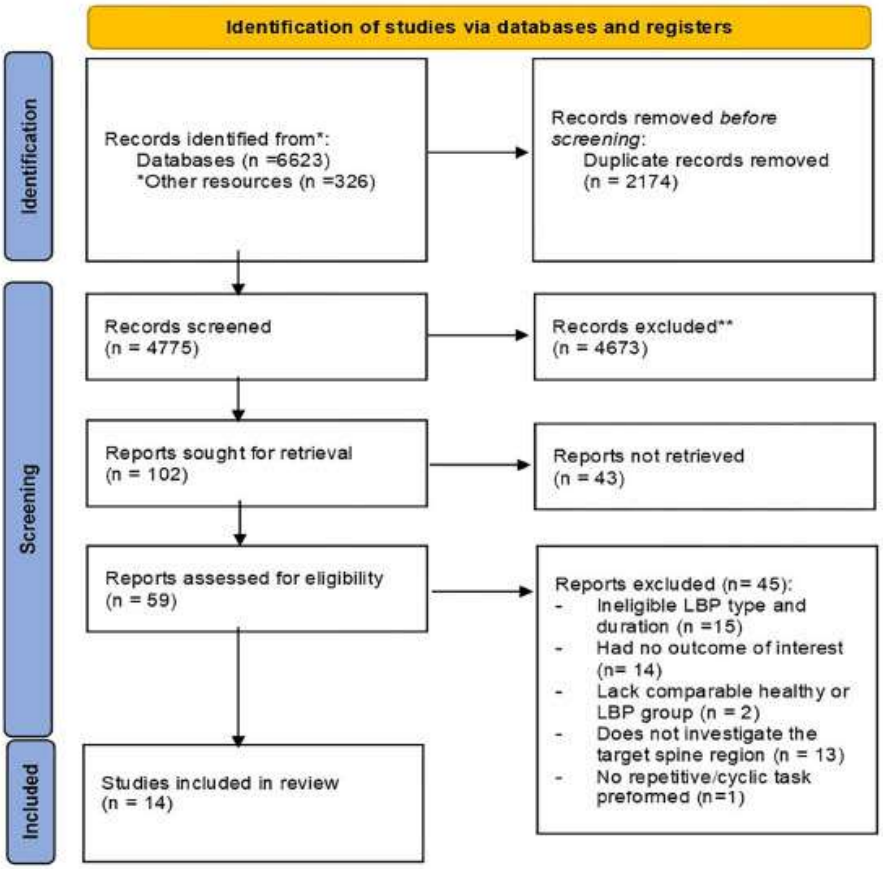


Fig 1. Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 flow diagram. *Other resources that were identified through searching the gray literature and hand search.

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tasks preformed, and the metrics used to analyse data. Therefore, meta-analysis was inappropriate and individual results are presented quantitatively using RevMan. The interpretation of the reported effect sizes were based on the mean difference where (0.0–0.2) considered small effect, (0.4–0.5) medium, and (0.8–3.0) large effect [63].

Type of task

Repeated flexion and extension. Three studies investigated movement variability during repeated flexion-extension task performed under symmetrical (n = 3) [49–51] or asymmetrical (n = 2) conditions [49, 50] (Fig 2). One study used a linear measure known as deviation phase (DP) to quantify the amount of intersegmental coordination variability [50]. The other two studies employed non-linear measures, with one study characterizing the structure of variability in angular displacement using maximum Lyapunov exponent (λmax) [49], and the other

Table 2. Demographic and clinical characteristics of included studies.

First Author	Sample size; sex (f/m); age (yrs); height (cm); weight (kg); BMI (kg/m^2)			LBP characteristics		
	LBP	Healthy control	Matching criteria for two groups	Intensity; duration	Disability level	Psychological status
1. Repeated Flexion and Extension task						
Graham et al. 2014 [49]	10; 6/4; 20.8 (1.4); 175.9 (14.0); 71.8 (14.1); NR	10; 6/4; 20.6 (1.0); 173.7 (11.1); 72.5 (12.0); NR	Sex; age; height; weight	NR; 24.4±23 months	ODI (0–50): 7.8 (3.5); RMDQ (0–24): 4.0 (2.1)	NR
Mokhtarinia et al. 2016 [50]	22; 0/22; 30.2 (6.1); 177 (7.7); 74.5 (7.7); 23.9 (3.3)	22; 0/22; 27.4 (5.1); 174 (8.2); 71.4 (10); 23.5 (3.5)	Age; height; weight	VAS (0–10) < 2; NR	NR	NR
Bauer et al. 2017 [51]	59; 29/30; 39.1 (12.8); NR; NR; 24.0 (3.6)	27; 15/12; 39.6 (11.6); NR; NR; 22.7 (2.8)	NR	NRS ≥ 1; NR	ODI > 8% moderate disability	STarT Back Screening Tool- psychological subscale: < 4
2. Lifting task						
Dideriksen et al. 2014 [19]	17; 10/7; 32.5 (9.6); 177. 4 (9.6); 74.3 (12.8); NR	17; 9/8; 29.7 (7.3); 174.8 (10.3); 69.2 (14.0); NR	Sex; age	NRS: 3.1 (2.2); 34.2 (29.3) months	ODI: 14.2% (7.2)	SF-36 (total) (0–100): 66.9 ± 12.2 Physical (0–100): 60.9 ± 14.2 Mental (0–100): 67.6 ± 14.1 TSK (17–68): 31.8 ± 5.9 PCS (0–52): 16.1 ± 8.5 STAI (20–80): 40.2 ± 7.1
Bauer et al. 2015 [52]	63; 31/32; 39.2 (12.5); NR; NR; 24.2 (3.9)	31; 17/14; 40.1(12.1); NR; NR; 22.7(2.9)	NR	NRS: 3.3 (1.5) ;NR	ODI > 8%, moderate disability	SBT psychosocial subscale (≥4 high risk): < 4
Moreno Catalá et al. 2018 [53]	*Non-athletes*: 15; 5/10; 27 (1); 178 (7); 78 (17.7); 24.3 (4.3) *Athletes*: 15; 5/10; 23 (2); 175 (10);72.9 (10.7); 23.6 (1.6) *Combined*: 30; 10/20; 25 (2.6); 176.5 (8.6); 75.5 (14.6); 23.9 (3.2)	*Non-athletes*: 14; 5/9; 24 (3); 175 (11); 70.3 (11.2); 22.7 (2.5) *Athletes*: 15; 5/10; 23 (3); 178 (9); 73.4 (13.4); 22.8 (2.4) *Combined*: 29: 10/19; 23.5 (2.9); 176.5 (9.9); 71.9 (12.2); 22.8 (2.4)	Age; height; weight	VAS: 3.92±1.70 (Non-athletes) , 4.54±1.82 (athletes), 4.2 ±1.8 (combined); ≥ 12 months	NR	NR
Pranata et al., 2018 [54]	*High disability (ODI > 20%)*:18; 12/6; 46.7 (11.8); 170 (10); 71.5 (14.0); 24.8 (3.8) *Low disability (ODI < 20%)*: 25; 11/14; 42.3 (11.1); 174 (10); 81.6 (19.0); 26.0 (5.0) *Combined*: 43; 23/20; 44.1 (11.5); 172.3 (10); 77.3 (17.6); 25.5 (4.5)	29; 17/12; 37.8 (11.5); 167 (10); 73.4 (17.6); 25.9 (5.6)	Sex; age; BMI	NRS (0–10): 4.5 ± 1.9 (high disability, 3.0 ± 1.6 (low disability), 3.6 ± 1.9 (combined) ; 155.2 ± 173.2 months (high disability), 110.2 ± 107.8 months (low disability), 129 ± 138.8 (combined)	ODI (0–100%): 34.4 ± 10.9 (high disability)13.2 ± 4.9 (low disability); 22 ±13.2 (combined)	NR
Fujii et al., 2022 [55]	31; 0/31; 30.5 (6.0); 172.7 (3.6); 65.5 (4.2); NR	20; 0/20; 28.1 (5.2); 172.0 (4.8); 66.7 (9.0); NR	NR	NRS in the past 4 wks (0–100): 3.6 (1.7); 14.7 (14.9) months	RMDQ (0–24): 2.1 (1.4)	TSK-11 (11–44): 21.9 (5.0). PCS-4 (0–16): 6.4 (3.9). Fre-BAQ (0–36): 7.5 (6.5)

(*Continued*)

Table 2. (Continued)

First Author	Sample size; sex (f/m); age (yrs); height (cm); weight (kg); BMI (kg/m^2)			LBP characteristics		
	LBP	Healthy control	Matching criteria for two groups	Intensity; duration	Disability level	Psychological status
3. Gait						
Vogt et al. 2001 [56]	*Male*: 21; NA; 36.3 (1.7); 173.3 (9.1); 77.8 (16.3); 25.8 (4.1) *Female*: 13; NA; 32.1 (3.4); 175.9 (5.6); 76.9 (12.5); 24.8 (3.3) *Combined*: 34; NA; 34.7 (3.2); 174.2 (7.9); 77.5 (13.1); 25.4 (3.7)	*Male*: 16; NA; 34.8 (5.2); 178.6 (4.7); 77.6 (6.5); 25.5 (2.4) *Female*: 6; NA; 29.4 (1.3); 170.3 (9.9); 71.5 (4.9); 23.7 (2.6) *Combined*: 22; NA; 33.3 (5.0); 176.3 (7.3); 75.9 (6.6); 25.0 (2.5)	NR	VAS (0–10): 3.7 (range, 3–5.3); NR	ODI: 27.67%; (range, 24–48%)	NR
Lamoth et al. 2006a [57]	19;11/8; 38 (21–52); 173 (154–188); 74.4 (49–97); NR	14; 5/9; 31 (20–46); 180 (158–198); 72.5 (52–105); NR	Sex; age; height; weight	VAS: 5.6 (3); 14.4 (3.5–36) months	RDQ: 10 (6)	TSK: 39 (6.8)
Lamoth et al. 2006b [58]	12; 7/5; 36.8 (10.9); 174 (11); 72.4 (14.5); NR	12; 5/7; 30±8.1; 180 (12); 73.3 (16.6); NR	Age; height; weight	NR; NR	NR	NR
Seay JF et al. 2011 [59]	14; NR; 35.71 (10.90); 171 (12); 73.94 (13.42); NR	14; NR; 29.90 (8.45); 169 (10); 63.94 (10.06); NR	Age; height; weight	VAS (1–10): 0.8 (1.4); NR	ODI (0–100%) : 7.9% (6.3)	NR
Ebrahimi et al. 2017 [60]	10; 5/5; 29.4 (6.38); 68.07 (12.92); 164.4 (8.19); NR	10; 5/5; 29.6 (5.64); 62.38 (13.12); 167.40 (7.36); NR	Sex, age, height, and weight	NRS: 5.1 (0.88); NR	ODI: 37.30% (12.66)	NR
4. Sit to stand to sit (STS) task						
Ippersiel et al. 2018 [61]	16; 11/5; 30 (9); NR; 78.6 (18.5); NR	21; 10/11; 27 (10); NR; 67.4 (10.0); NR	NR	NPRS (0–10): 3.4 (1.1); 109.9 (113.5) months	ODI: 25.3%(7.4)	NR

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study assessing the structure of variability in both angular displacement and velocity using percentage determinism (DET%), and sample entropy (SaEn) [51]. It is worth noting that λmax was defined as a measure of local stability, where lower λmax values is associated with higher stability [49], while DET% was described as a measure of predictability and SaEn as a measure of complexity [51].

Out of a total of eight measurements, only two measures from one study showed a significant difference in variability indices between people with and without LBP [51]. Those with LBP showed a higher level of complexity and less predictability in angular velocity (as indicated by high SaEn), but greater predictability in angular displacement (as indicated by high DET%). A more pronounced effect was observed for angular velocity (with a medium effect size) compared to angular displacement (with a small effect size). However, this effect was not reported in the study, as the main comparison focused on detecting the effect of fatigue using a linear mixed model. Therefore, the effect of pain was only measured based on the pre-fatiguing condition using the reported means, SDs, and sample sizes, which was significant only for SaEn on angular velocity ($p = <0.001$). Overall, only one of the three studies reported a small to medium effect of LBP status on variability measures during the repetitive trunk flexion and extension task, indicating a reduction in predictability and an increase in complexity.

Table 3. Measurement protocol of included studies.

First Author	Task preformed	Instrument used	Spine region assessed	Outcome measures	*P* value
1. Repeated Flexion and Extension task					
Graham et al. 2014 [49]	Two randomized trials, symmetric and asymmetric, of 30 repetitive and continuous trunk flexion and extension movements from standing position, with a constrained pelvis and their hands held together	Electromagnetic motion sensors (Liberty, Polhemus, Colchester, VT, USA)	Lumbar spine (over T12 and S1)	Maximum Lyapunov exponent, λmax (Local dynamic spine stability)	**Dynamic stability:** **Group:** $p = 0.440$
Mokhtarinia et al. 2016 [50]	30 cycles of repeated trunk flexion–extension (touching target placed at knee level followed by returning to upright position)	3D video-motion analysis system (VICON, Oxford, UK)	Lumbar–pelvis (T10-PSIS-ASIS)	Deviation phased DP (sagittal plane)	**DP (Degree):** **Group:** $p = 0.75$
Bauer et al. 2017 [51]	Repeated trunk flexion and extension test in sitting position	Inertial measurement unit (IMU) system (Valedo ®Motion, Hocoma AG, Volketswil, Switzerland)	Lumbar between 1st lumbar and 2nd sacral vertebra	Determinism% and Sample entropy of angular displacement and velocity	**Pre-Fatigue condition:** **Angular Displacement** **Group:** **%DET:** $p = 0.138$ **SaEn:** $p = 1.0$ **Angular velocity** **Group:** **%DET:** $p = 0.57$ **SaEn:** $p = <0.001^*$
Dideriksen et al. 2014 [19]	Repetitively move a box (5 kg) between two shelves, located at knee and shoulder height	Epionics SPINE (Epionics Medical GmbH, Potsdam, Germany) with two sensor strips, each with 12 evenly spaced angle sensors (25 mm apart from one another); The bottom of the strip located at the posterior superior iliac spine (PSIS)	From PSIS 30 cm upward covering the whole spine	Determinism%	**%DET** **Group:** Average $p = 0.54$
2. Lifting task					
Bauer et al. 2015 [52]	Pick up a box from standing position, 10 cycles	Inertial measurement unit IMU system (ValedoMotion, Hocoma AG, Volketswil, Switzerland)	Lumbar between 1st lumbar and 2nd sacral vertebra	Recurrence (REC) and Determinism (DET) of angular displacement, velocity, and acceleration	**Angular displacement (AD)** **Group:** REC AD: $p = 0.018$ DET AD: $p = 0.01^*$ **Angular velocity (AV)** REC AV: $p = 0.03^*$ DET AV: $p = 0.05^*$ **Angular acceleration (AA)** REC AA: $p = 0.03^*$ DET AA: $P = 0.05^*$
Moreno Catalá et al. 2018 [53]	Lifting task, in which a pot (1.5 kg) was cyclically moved back and forth between two tables of different heights (40 cycles); participant standing in the middle of two tables	Vicon 624 system (Vicon Motion Systems, United Kingdom)	Lumbar-pelvis: Region between L4/L5 disk space and ninth thoracic vertebrae.	Maximum Lyapunov exponent (λmax)	**Dynamic stability (λmax):** **Group:** $p = 0.136$

(*Continued*)

Table 3. (Continued)

First Author	Task preformed	Instrument used	Spine region assessed	Outcome measures	*P* value
Pranata et al., 2018 [54]	Lifting an 8-kg kettlebell up to the level of their abdomen using a self-selected pace and technique; repeated twice	12-camera Optitrack Flex 13 motion analysis system (NaturalPoint, Corvallis, OR)	Lumbar-pelvis in the sagittal plane	Deviation phase (DP)	**DP lumbar-hip (Degree):** **Group:** $p = 0.13$
Fujii et al., 2022 [55]	Lifting a box (520 × 365 × 305 mm) placed on the ground as quickly as possible to waist-height. In three different conditions	A three-dimensional (3D) motion capture system with a four-charge-coupled device (CCD) camera (KinemaTracer, KisseiComtec, Matsumoto, Japan).	Upper and lower lumbar regions. (L3 spinous process and S1 spinous process)	Deviation phase (DP)	**DP (Degree):** **Flexion phase:** **Group:** $p = 0.10$ **Extension phase:** **Group:** $p = 0.57$
3. Gait					
Vogt et al. 2001 [56]	Walking on a motorized treadmill at 4.5 km/h; data from a 30-second interval recorded while walking for approximately 3 minutes	Treadmill: a motorized treadmill (HPCosmos, Germany); Motion: three-dimensional ultrasonic movement analysis system (Zebris CMS 70, Germany)	Thoracolumbar (markers placed on T12 and S1)	Coefficient of variation (CV)	**Stride-to-Stride CV:** **Group:** $p < 0.001$*
Lamoth et al. 2006a [57]	Walking on a treadmill at a self-selected walking velocity succeeded by increasing velocity from 1.4 km/h to a maximally attainable walking velocity of up to 7.0 km/h	3D active marker movement registration system (Optotrak 3020, Northern Digital, Ontario, Canada)	T3, L2 spinous processes, and the sacrum (between posterior superior iliac spine PSIS)	SD relative phase between lumbar and pelvis rotations (transverse and frontal plane)	**Relative phase variabilit (Degree):** **Group:** Transverse plane: $p = 0.04$* Frontal plane: $p < 0.01$*
Lamoth et al. 2006b [58]	Walking on a treadmill at six velocities in a fixed order: 6.2, 1.4, 3.8, 5.4, 2.2, and 4.6 km/h	3D active marker movement registration system (Optotrak 3020, Northern DigitalTM, Ontario, Canada)	Third thoracic vertebra (T3), second lumbar vertebra (L2), and the sacrum	SD relative phase between lumbar and–pelvis rotations (transverse and frontal plane)	**Relative phase variability (Degree):** **Group:** Transverse plane: $p = 0.03$* Frontal plane: $p < 0.01$*
Seay JF et al. 2011 [59]	Walking (at various speeds systematically increased from 2.88km/h in increments of 1.8km/h to 13.68 km/h	Treadmill: (Frappier Acceleration, Fargo, ND, USA and Advanced Mechanical Technologies, Incorporated, Waltham, MA, USA); Motion: Three-dimensional kinematic data were collected using eight high-speed cameras (Motion Analysis Corp., Santa Rosa, CA)	Pelvis–trunk (T12 L1 -L5 S1 inter-vertebral joint space) in sagittal, frontal and transverse plane	SD relative phase	**Relative phase variability (degree):** **Group:** **Sagittal:** Walking: $p = 0.662$ Running: $p = 0.122$ **Frontal:** Walking: $p = 0.402$ Running: $p = 0.985$ **Transverse:** Walking: $p = 0.203$ Running: $p = 0.022$*
Ebrahimi et al. 2017 [60]	Walking barefoot along an 8-m walkway at a comfortable self-selected speed; at least 20 complete gait cycles for each limb captured	An eight-camera motion analysis system (Proreflex, Qualisys Track Manager® Ltd., Gothenburg, Sweden)	Upper and lower back–pelvis.	Deviation phase over stance and swing (sagittal plane)	**DP (degree):** **Group:** Stance: $p = 0.049$* Swing: $p = 0.008$*
4. Sit to stand to sit (STS) task					

(*Continued*)

Table 3. (Continued)

First Author	Task preformed	Instrument used	Spine region assessed	Outcome measures	Pvalue
Ippersiel et al. 2018 [61]	Sit to stand to sit (STS) task with arms crossed over chest, including standing upright from sitting and return to sitting as quickly as possible, 10 trials	An electromagnetic TrakSTAR motion capture system with model 800 sensors (Ascension Technology, Milton, VT, USA)	The lower lumbar spine (L3-S1) and upper lumbar spine (T12-L3)	Deviation phase DP (sagittal plane)	DP (degree): L3S1-T12L3: Group: $p = 0.147$

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Lifting. Five of the included studies investigated movement variability during lifting tasks. Two of these studies [54, 55] used a linear measure, specifically DP, while the remaining three studies [19, 52, 53] utilized non-linear measures, including recurrence rate (REC), DET, and λmax (Fig 3).

All studies, apart from one [52], did not show differences for people with LBP for movement variability during lifting. Bauer et al. 2015 showed less predictable lumbar movement patterns, as indicated by a significant reduction in determinism for various movement variables, including angular displacement, velocity, and acceleration [52].

Even though the forest plot in the study of Pranata et al. 2018 showed a significant effect (with a large size), the paper itself reported no effect for either subgroups recruited (i.e. LBP patients with low or high disability) [54]. This inconsistency between the forest plot results and the original study could be due to the statistical model's correction of variables for age effects. The same contrast was also obtained when LBP subgroups were compared separately with controls. In this case, people with LBP with low disability showed a significant effect. Overall, only one out of five studies reported a medium to large effect of the presence of LBP on movement variability during lifting tasks, characterized by a reduction in the predictability of lumbar movement.

Gait (walking and running). Five studies included in this review used linear measures to quantify gait variability (Fig 4). One study [56] used angular displacement, while the other four studies [57–60] used a combination of angular displacement and velocity as coordination indices, specifically the continuous relative Fourier phase (RP), continuous relative phase (SD RP).

All five included studies reported some changes in at least one of their outcomes, with four studies finding a decrease [57–60] and two finding an increase in variability of gait (during

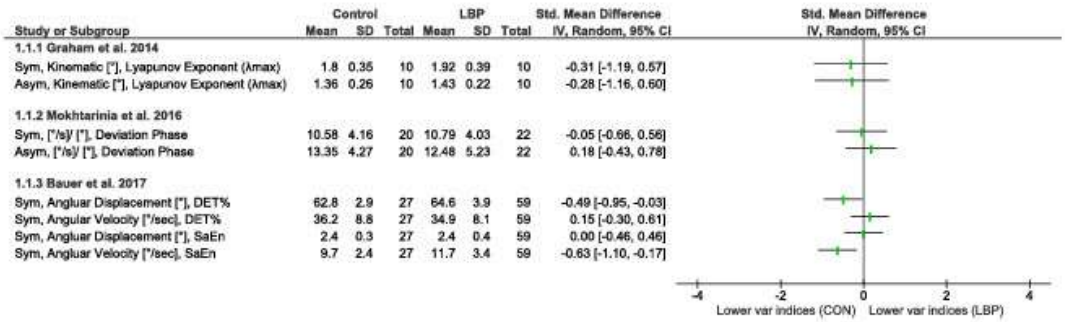


Fig 2. Differences in movement variability between people with LBP and healthy controls (CON) while preforming repeated flexion and extension tasks. Abbreviations: Sym: symmetric; Asym: Asymmetric; %DET: Percentage determinism; SaEn: Sample entropy; Var: Variability.

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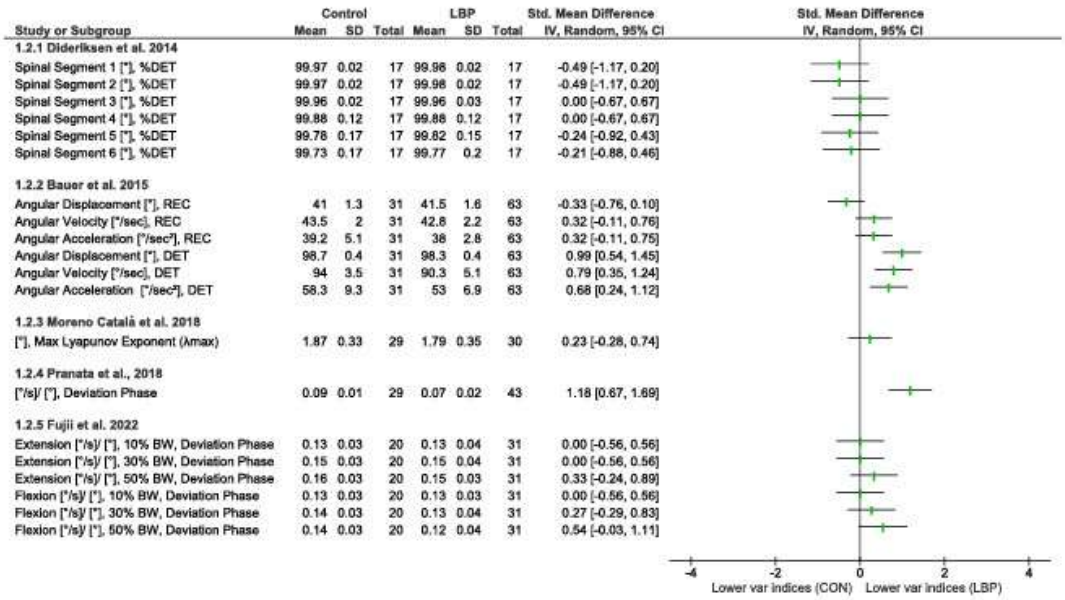


Fig 3. Differences in movement variability between people with LBP and healthy controls (CON) while preforming lifting tasks. Abbreviations: DET: Determinism; REC: recurrence rate; Var: Variability.

https://doi.org/10.1371/journal.pone.0287029.g003

walking or running) [56, 58]. Even though the forest plot showed no effects [60], the original article reported a significant decrease in variability. The discrepancy could be due to the authors' use of a non-parametric test in their study since the data failed to fit a normal distribution. However, the most prominent finding was a decrease in variability of lumbar-pelvis coordination in the transverse plane and an increase in the frontal plane in those with LBP compared to controls regardless of walking speed [57, 58]. Overall, all studies reported a change in movement variability in people with LBP compared to healthy controls, with effect sizes ranging from medium to large.

Sit to stand to sit (STS) task. Only one of the included studies was categorized under this task (Fig 5). This study investigated movement variability during a repeated sit-to-stand-to-sit (STS) task [61], which divided the task into four periods: start, up, down, and end. The authors used DP to describe the amount of inter-joint coordination variability.

For the lumbar region, no effect of LBP status was observed over the full task. However, there was a significant period effect characterized by greater variability over the start and end period of the STS task. No group or interaction effect was observed.

Methodological quality assessment

Five of the included studies [19, 50–52, 61] were rated as high-quality studies that met most of the quality criteria (75% to 83%) (Table 4). On the other hand, nine studies [49, 53–60] partially met the quality criteria (67%) and were rated as a moderate quality studies. The two most common weaknesses occurred in the report of the treatment history of those with LBP (item 6), and sample size justification or power description (item 12), and less commonly, representativeness of LBP and control groups (item 8).

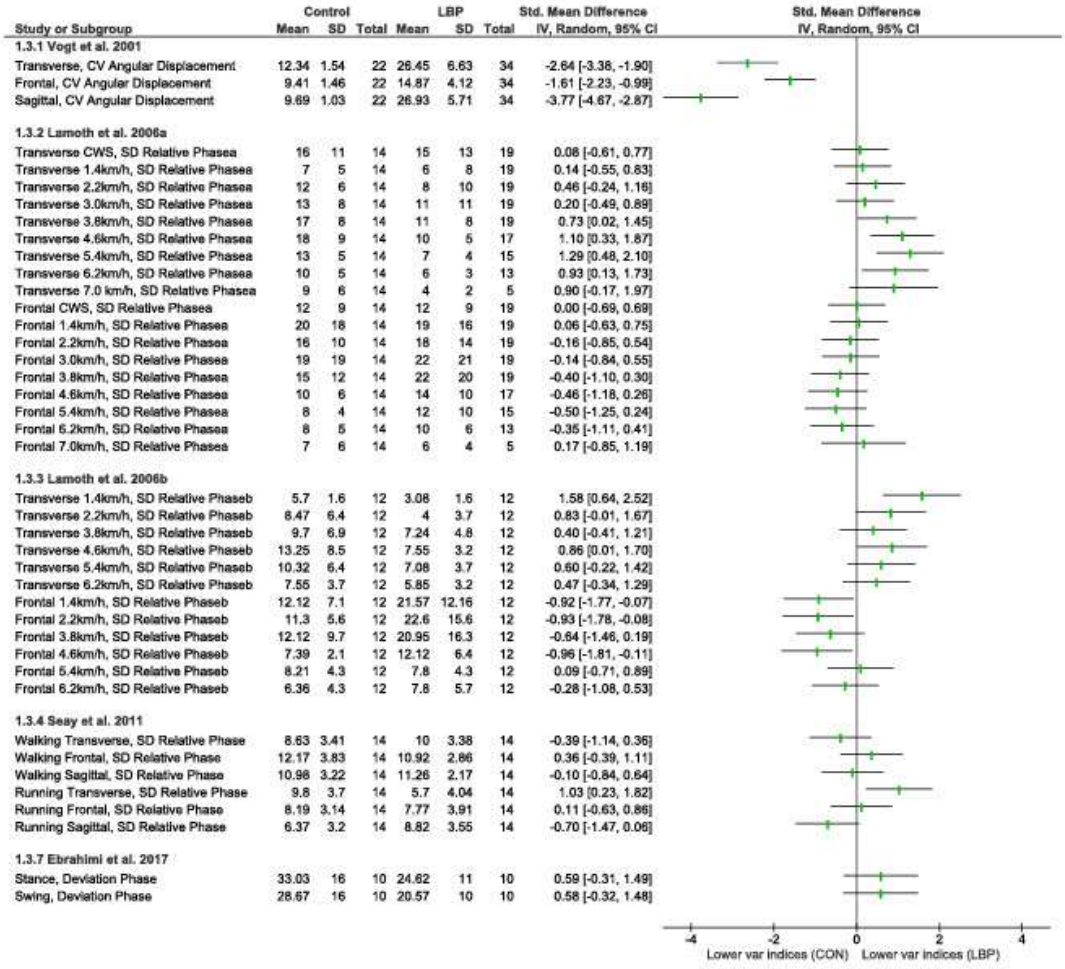


Fig 4. Differences in movement variability between people with LBP and healthy controls (CON) during walking or running tasks. Abbreviations: CV: Coefficient of Variation; SD: Standard deviation: Var: Variability.

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Level of evidence (GRADE)

The main outcome measures from individual studies were grouped per task type as domains and the obtained evidence was narratively described across studies. The quality of evidence per domain was summarised in accordance with GRADE and is reported in Table 5.

The overall quality of evidence was downgraded from low to very low for all domains mostly due to issues concerning imprecision of the included studies, inconsistency between effects, and to a lesser extent due to indirectness and potential publication bias. Downgrading the quality of evidence based on imprecision, was addressed using the optimal information size rule (OIS) to present the required sample size for the continuous outcomes that was used

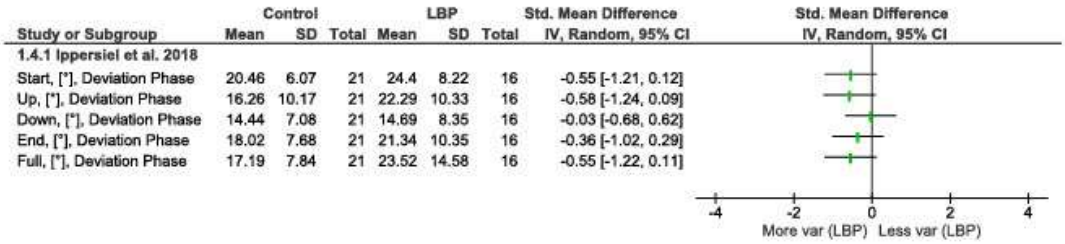


Fig 5. Differences in movement variability between people with LBP and healthy controls (CON) during sit to stand task. Abbreviations: SD: Standard deviation: Var: Variability.

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in the included studies. The usual standards of α (0.05) and β (0.20), was used with an effect size of 0.2 standard deviations, representing a small effect, which required a total sample size of approximately 400 (200 per group) [64]. However, the included studies had a maximum sample size of 94 participants, which suggests a small sample size, and resulted in a wide confidence interval (CI) around the estimate of the effect as detected by the forest plot. With regards to inconsistency, all domains showed serious concerns in heterogeneity of the results except for the repeated flexion and extension tasks that presented a significant overlap of confidence intervals as observed in the forest plot, suggesting minimal variation in effect sizes.

Discussion

This review is the first to provide a comprehensive analysis of observational studies that investigated whether thoraco-lumbar and lumbo-pelvic kinematic variability is altered in people

Table 4. Quality rating instrument using modified Downs and Black Scale (adjusted specifically for the current review).

Studies	*Item*												*Total/12*	*Percentage/ 100%*
	Reporting							*External validity*	*Internal validity/bias & confounding*			*Power*		
	1	2	3	4*	5*	6*	7	8	9	10	11*	12		
	q.1 D&B	*q.2 D&B*	*q.3D&B*				*q.7D&B*	*q.11 D&B*	*q.16 D&B*	*q.20 D&B*		*q.27 D&B*		
Graham et al. 2014 [49]	1	1	1	1	1	0	1	0	1	0	1	0	8	67
Mokhtarinia et al. 2016 [50]	1	1	1	1	1	***0***	1	0	1	1	1	0	9	75
Bauer et al. 2017 [51]	1	1	1	1	1	0	1	1	1	1	1	0	10	83
Dideriksen et al. 2014 [19]	1	1	1	1	1	0	1	1	1	0	1	0	9	75
Bauer et al. 2015 [52]	1	1	1	1	1	0	1	1	1	1	1	0	10	83
Moreno Catalá et al. 2018 [53]	1	1	1	1	1	0	1	0	1	0	1	0	8	67
Pranata et al., 2018 [54]	1	1	1	1	1	0	1	0	1	0	1	0	8	67
Fujii et al. 2022 [55]	1	1	1	1	1	0	1	0	1	***0***	0	1	8	67
Vogt et al. 2001 [56]	1	1	1	1	1	0	1	0	1	0	1	0	8	67
Lamoth et al. 2006a [57]	1	1	1	1	1	0	1	0	1	0	0	1	8	67
Lamoth et al. 2006b [58]	1	1	1	1	1	0	1	0	1	0	1	0	8	67
Seay JF et al. 2011 [59]	1	1	1	1	1	0	1	0	1	0	1	0	8	67
Ebrahimi et al. 2017 [60]	1	1	1	1	1	0	1	0	1	0	1	0	8	***67***
Ippersiel et al. 2018 [61]	1	1	1	1	1	0	1	1	1	1	1	***0***	10	83

https://doi.org/10.1371/journal.pone.0287029.t004

Table 5. Quality of evidence assessment based on Grading of Recommendations, Assessment, Development and Evaluation (GRADE) criteria.

Movement variability based on the task preformed	Number of LBP patients (studies)	Risk of bias (D&B scale score)	Inconsistency	Indirectness	Imprecision	Number of participants		Publication bias	Overall Quality of Evidence
						LBP group	Control group		
Repeated Flexion and Extension tasks	91 (3) Graham 2014 Mokhtarinia et al. 2016 Bauer et al. 2017	Not serious 67% 75% 83%	Not serious	Serious[b] ↓	Serious[c] ↓	 10 22 59	 10 22 27	Suspected[d]	Very low
Lifting tasks	184 (5) Dideriksen et al. 2014 Bauer et al. 2015 Moreno Catalá et al. 2018 Pranata et al. 2018 Fujii et al. 2022	Not serious 75% 83% 67% 67% 67%	Serious[a] ↓	Serious[b] ↓	Serious[c] ↓	 17 63 30 43 31	 17 31 29 29 20	Suspected[d]	Very low
Gait	89 (5) Vogt et al. 2001 Lamoth et al. 2006a Lamoth et al. 2006b Seay et al. 2011 Ebrahimi et al. 2017	Not serious 67% 67% 67% 67% 67%	Serious[a] ↓	Serious[b] ↓	Serious[c] ↓	 34 19 12 14 10	 22 14 12 14 10	Suspected[d]	Very low
Sit to stand to sit (STS) task	16 (1) Ippersiel et al. 2018	Not serious 83%	Serious[a] ↓	NA*	Serious[c] ↓	 16	 21	Suspected[d]	Very low

GRADE: High quality: very confident that the true effect lies close to that of the estimate of the effect and further research is very unlikely to change. Moderate quality: moderately confident in the effect estimate and further research may change the estimate. Low quality: limited confident in the effect estimate and further research is very likely to have an important impact to change the estimate. Very low quality: Any estimate of effect is very uncertain.

[a] ↓High level of heterogeneity; we downgrade one level due to variability in results or inconsistency between effects.

[b] ↓Evidence was not directly comparable to the question of interest; we downgrade one level due to the variety of outcome measurement tools including the used motion analysis systems and the analysis metrics.

[c] ↓Few participants and few events: we downgrade one level due to the wide confidence interval (CI) around the estimate of the effect (as estimated by forest plot).

[d]Limited number of observational studies with small sample size as well as asymmetrical distribution of observations on the funnel plot

NA* not applicable: Only one study.

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with non-specific chronic LBP compared to asymptomatic individuals, while preforming repetitive cyclic functional tasks. Asymptomatic people typically exhibit a normal range of motor variability when performing functional tasks [65], however, those with LBP may display motor adaptations resulting in altered movement variability [66]. Movement variability is known to range from complete repeatability to excessive variability in both space and time [23]. However, the degree of adaptive variability in the trunk during repetitive functional tasks among individuals with LBP is not well established which emphasises the need to synthesise the literature for a better understanding of the optimal adaptive variability for people with chronic LBP.

To facilitate interpretation, this review grouped the results into four categories based on the tasks used to investigate movement variability; repetitive trunk flexion and extension, lifting, gait, and in one study, sit-to-stand-to-sit. While the overall quality of evidence in this review was rated as very low, due to the inclusion criteria of observational studies with small sample sizes, all included studies were of high to medium methodological quality, with no study rated as low quality. However, heterogeneity in the metrics used for analysis and effect sizes contributed to downgrade the quality of evidence.

Although this review sub-grouped the evidence for better interpretation, the choice of metrics within each group was crucial for understanding changes in movement variability. As mentioned previously, linear and non-linear metrics capture distinct aspects of movement variability that may vary independently from one another [23]. For example, an increase in the structure of variability does not necessarily indicate an increase in the amount of variability. In the reviewed studies, changes in the structure of variability were commonly described using terms such as predictability or repeatability, rather than an increase or decrease in variability. Conversely, the amount of variability was typically reported simply an increase or decrease.

Differences in movement variability between people with and without chronic LBP

This review found that people with chronic non-specific LBP move their lumbar spine in a complex and less predictable way, likely as an adaptive response to pain, particularly noted as a change in the angular velocity of the trunk during repetitive flexion and extension [49–51]. Similarly, the task of lifting showed a general reduction in the predictability of angular displacement, velocity and acceleration [19, 52–55]. Although this result was drawn from non-linear metrics, for a comparable result, less predictable behaviour can be indirectly described as an increase in the amount of variability. The nature of both tasks similarly involves predetermined (loaded/unloaded, symmetrically/ asymmetrically) repetitive trunk movements which resulted in people with LBP moving their lumbar spine in a more variable. This finding is consistent with a previous review that found a common feature among individuals with chronic or mechanical LBP was increased kinematic spinal movement variability [21]. Despite this consistency, these findings should be interpreted with caution due to the heterogeneity of the metrics used, which are conceptually different [20]. Moreover, the level of evidence supporting this observation is very low, indicating a lack of confidence in the estimate of this result.

Given that walking is one of the most common activities of daily living, numerous studies have examined motor variability during gait [27]. Our review found that people with chronic non-specific LBP experience changes in kinematic variability during gait regardless of walking speed, which was primarily in coordination patterns of movement; however, the direction of change was not consistent [56–60]. Gait studies typically investigate motor adaptations across multiple planes of movement, which provide a more comprehensive understanding of the direction of motor control changes. For instance, the reviewed studies reported more rigid and less variable coordination between transverse lumbo-pelvic rotations in people with LBP compared to healthy controls, whereas the coordination between spinal regions in the frontal plane was less rigid and more variable. This finding aligns with a previous review that found altered motor control in people with chronic LBP during gait, showing higher stride-to-stride kinematic variability. However, this was not surprising considering that most of the studies included in the previous review were also eligible for our review [26]. The level of evidence was rated very low, although the evidence was based on linear metrics of variability only, this was mostly due to the small sample sizes that led to wide CIs around the estimate of the effect.

There was limited evidence examining the sit-to-stand-to-sit task. However, similar to other tasks such as gait, the evidence was based on the amount of inter-joint coordination variability. Yet, no difference was observed in the adaptive variability during task performance between people with and without chronic LBP [61].

LBP characteristics and movement variability

This review analysed 14 observational studies with a total of 380 participants with non-specific chronic LBP to determine the level of adaptive variability during various repetitive functional

activities. Although the type of LBP was predetermined as chronic non-specific, there was no restrictions on LBP duration, intensity, or level of disability. However, the level of both LBP intensity and disability was minimal across studies, and some of the functional tasks may not have been challenging enough to evoke noticeable changes in movement variability. Although previous research has established a connection between pain-related threat beliefs and disability with trunk kinematics in people with LBP, there is a scarcity of research exploring the impact of factors like fear-avoidance behaviour/beliefs and catastrophic thinking on kinematic variability [67]. Only one study in the current review investigated the correlation between pain-related fear and trunk inter-joint coordination variability in people with chronic LBP [55]. Therefore, further studies are needed to explore the relationship between movement variability and pain-related psychological factors.

Methodological considerations

The current review adhered to rigorous methodology outlined in a predefined and published protocol [32]. Screening, quality assessment, and data extraction was performed independently by two reviewers. In addition, unlike previous scoping reviews that did not assess the overall level of evidence [20, 21], the current review utilized GRADE to evaluate the overall level of evidence. Although meta-analysis was not applicable, we presented our findings quantitatively using forest plots to support the narrative synthesis.

There are some limitations that should be acknowledged. The current review included a limited number of observational studies with small sample sizes, which could have led to potential publication bias. Additionally, there are no established recommendations for evidence synthesis of observational studies, which makes it challenging to draw definitive conclusions based on the observational nature of the presented evidence [68].

Conclusion

Despite very low-level evidence, people with chronic non-specific LBP exhibited altered motor adaptability, as indicated by differences in kinematic movement variability during repetitive functional tasks. However, the direction of these changes in movement variability was not consistent across individuals with chronic LBP. This systematic review highlights the importance of standardizing terminology for assessing kinematic variability and emphasizes the need for future research to consider the conceptual differences between different metrics.

Supporting information

S1 Table. Preferred reporting items for systematic reviews and meta-analyses checklist-PRISMA.
(DOCX)

S2 Table. Inclusion and the exclusion criteria of the included studies.
(PDF)

S3 Table. Detailed description of the task preformed in the included studies.
(PDF)

S1 File. Search strategy used in MEDLINE (OVID interface).
(PDF)

S2 File. Excluded studies with reasons.
(XLSX)

Author Contributions

Conceptualization: Amal M. Alsubaie, Eduardo Martinez-Valdes, Deborah Falla.

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Appendix 3 - PRISMA Checklist for *Chapter Two*

PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	Page 26
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	Page 27
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	Page 28
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	Page 29
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	Page 30-32
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	Page 32,33
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	Page 32,33
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	Page 33,34
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	Page 34
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	Page 34
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	Page 34
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	Page 34,35
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	Page 35
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	Page 35

1

	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	Page 35
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	Page 35
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	Page 35
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	Page 35
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	N/A
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	Page 36



PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	Page 36
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	Page 36,37
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	Page 36,37
Study characteristics	17	Cite each included study and present its characteristics.	Page 38-54
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	Page 54,55
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	Page 43-55
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	Page 54,56
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	Page 54,56
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	Page 54,56
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	N/A
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	N/A
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	Page 57-59
DISCUSSION			

Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	**Page 59-2**
	23b	Discuss any limitations of the evidence included in the review.	**Page 61**
	23c	Discuss any limitations of the review processes used.	**Page 62,63**
	23d	Discuss implications of the results for practice, policy, and future research.	**Page 63**
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	**Page 30**
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	**Page 30**
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	**N/A**
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	**Page 26**
Competing interests	26	Declare any competing interests of review authors.	**Page 26**
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	**Page 26**

From: Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi:10.1136/bmj.n71 For more information, visit: www.prisma-statement.org.

Appendix 4 - Alsubaie et al. (2021b)

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Trunk control during repetitive sagittal movements following a real-time tracking task in people with chronic low back pain

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ABSTRACT

Precision of trunk movement has commonly been examined by testing relocation accuracy rather than evaluating accuracy of tracking dynamic movement. In this study we used a 3-D motion capture system to provide a novel real-time tracking task to assess trunk motor control at varying movement speeds between people with and without chronic non-specific low back pain (LBP). Eleven asymptomatic volunteers and 15 participants with chronic non-specific LBP performed 12 continuous cycles of trunk flexion–extension following real time visual feedback, during which, trunk motion was measured using eight optoelectronic infrared cameras. Significant time differences between the feedback and actual trunk motion were found between groups ($P = 0.001$). Both groups had similar variability of tracking accuracy when following the feedback ($P > 0.05$). However, tracking variability at a slow speed correlated ($P = 0.03$; $r = 0.55$) with the Fear-Avoidance Beliefs Questionnaire (FABQ) scores in those with LBP. This study shows that both asymptomatic people and individuals with LBP displayed anticipatory behaviour, however, the response of those with LBP was consistently delayed in tracking the visual feedback compared to the asymptomatic group. Additionally, the extent of variability of tracking accuracy over repeated tracking cycles was associated with the degree of fear of movement in people with LBP.

1. Introduction

Repetitive sagittal trunk movement represents an occupational risk factor since it can lead to cumulative spinal loading even when performed with no or minimal weight [Coenen et al., 2014]. A further occupational risk factor is performing working tasks as quickly as possible, which is especially the case for self-paced work [Dempsey et al., 2010]. Cumulative spinal loads from fast paced repetitive trunk movements can be associated with the development of low back pain (LBP) [Coenen et al., 2013], a condition which is known to be a major health problem worldwide [Balagué et al., 2012].

People with chronic LBP often present with impaired trunk motor control which may contribute to the maintenance or perpetuation of their symptoms [Ghamkhar and Kahlaee, 2019, Sung et al., 2015]. Motor control impairments in people with LBP could be partially attributed to deficits in lumbar proprioception [Lee et al., 2010, Tong et al., 2017]. Indeed, it is expected that any proprioceptive impairment associated with LBP will affect the precise control of the trunk and could potentially lead to poorer quality of movement [Lee et al., 2010, Willigenburg et al., 2013].

Proprioception is commonly measured by quantifying the repositioning error when attempting to replicate predetermined positions in space [Newcomer, 2000]. Yet, repositioning tests for proprioception may partially rely on memory recall of the starting position or other prescribed position which may influence error detection [Lee et al., 2010]. It has been suggested that proprioceptive deficits may be more apparent during the performance of tracking or aiming tasks [Willigenburg et al., 2013]. To our knowledge, no study has tested tracking tasks using real-time visual feedback in order to investigate proprioception in the form of movement precision in people with LBP, yet this has been performed in asymptomatic people [Mousavi et al., 2009, Sheikhzadeh et al., 2008]. In these previous studies, the tasks were performed using an isokinetic dynamometer where the subject is constrained and their exertion level likely limited to a certain extent.

In the present study, we apply a novel real-time tracking task using a 3-D motion capture system to allow individuals to complete the tracking

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task with more natural movement. We assess the precision of trunk control during repetitive flexion–extension tasks with varying speed to compare the 1. Temporal delay of spinal movement (temporal accuracy), 2. Variability of tracking accuracy (spatial accuracy) and 3. Muscle activation and co-contraction in people with and without chronic non-specific LBP. A further objective was to assess for the presence of correlations between these outcome measures and levels of pain intensity, disability and fear of movement in those with chronic non-specific LBP. Based on previous findings which show that people with LBP tend to move slower with a stiffer trunk [Laird et al., 2019, Vaisy et al., 2015, van Dieën et al., 2003], we hypothesized that people with LBP will be slower at tracking and that they will present with greater co-contraction of their trunk muscles when performing repetitive tasks.

2. Methods

2.1. Design

This single session, cross-sectional study was conducted at the Centre of Precision Rehabilitation for Spinal Pain (CPR Spine), University of Birmingham, UK. Ethical approval for the study was granted by the Ethics Committee of the School of Sport, Exercise & Rehabilitation Sciences (CM 071217–1) and the study was conducted according to the Declaration of Helsinki. All participants provided written informed consent. The study is reported in line with the STROBE guidelines.

2.2. Participants

Eleven asymptomatic volunteers (8 men), and fifteen participants with chronic non-specific LBP (9 men) were enrolled in this study. Participants had to be between 18 and 55 years old and all individuals were recruited from students and staff of the University of Birmingham and via the Spinal Pain Register of the CPR Spine.

Asymptomatic participants were included in the study if they did not have back or lower limb pain/injury over the past three years that limited their functional abilities and/or which required treatment. People with chronic non-specific LBP were recruited if they had back pain that persisted for at least 3 months with pain experienced on at least half the days in the past 6 months [Dionne, 2008]. People with LBP related to trauma, fractures, spinal stenosis, or radicular pain were excluded. They were also excluded if they were receiving active treatment for their LBP within the last 3 months. Participants from both groups were excluded if they had concurrent systemic disorders, a history of chronic respiratory or neurological problems, spinal deformity or surgery, cardiovascular conditions and pregnancy.

2.3. Questionnaires

At the beginning of the session, the participants with LBP were asked to complete the following questionnaires to gather population statistics; The Oswestry Disability Index (ODI) questionnaire was used which is a reliable measure of disability relating to back pain [Fairbank and Pynsent, 2000]. The Fear-Avoidance Beliefs Questionnaire (FABQ) was used to asses any fear of movement related to pain using both physical activity (PA) and work (W) scales [Waddell et al., 1993]. A general questionnaire was issued to assess LBP characteristics, including pain intensity over the past four weeks (Visual Analogue Scale, VAS, with 0–10 cm as anchor points for no pain and the worst pain imaginable, respectively) and duration of symptoms. Current pain intensity was also quantified at the time of testing on a VAS.

2.4. Movement analysis and electromyography

Trunk motion was acquired using eight optoelectronic infrared cameras with a resolution of 2,2 Mpixels (2048 × 1088pxs) (BTS SMART-Suite Motion Capture System by BTS Bioengineering, Italy). Seventeen spherical retroreflective markers (14 mm) were used to construct 3D kinematic data of the trunk based on a modified model of marker placement described previously to define seven trunk segments [Preuss and Popovic, 2010]. Using double sided tape, markers were placed on the following anatomical landmarks which were identified by palpation to create two trunk segments; thoracic and lumbar segments [Sanderson et al., 2019]: the modified model included two markers on the right and left acromion, posterior superior iliac spines (PSIS), anterior superior iliac spines (ASIS), and iliac crests (IC). In addition to unilateral markers on spinous processes of 3rd thoracic (T3), 3rd lumbar (L3). And bilateral markers to the spinous process of 7th cervical (C7), 6th thoracic (T6), 9th thoracic (T9), and 12th thoracic (T12).

Surface electromyography (sEMG) was acquired using a wireless sEMG system (BTS FREE EMG 1000, sampling rate 1000 Hz, bandwidth 10–500 Hz); signals were detected with single-differential sEMG probes (Ambu WhiteSensor Ag/Ag–Cl disks size: 36 mm × 40 mm). An inter-electrode distance of 20 mm was chosen, following the SENIAM recommendations [Hermens et al., 2000]. sEMG was acquired from the lumbar erector spinae (ES) and obliques externus abdominis muscles (OEA) bilaterally. The electrodes for OEA muscle were placed approximately 15 cm lateral to the umbilicus and for ES muscle 3 cm lateral to L3 spinous process [Radebold et al., 2000]. Prior to the application of the electrodes, the skin was prepared by shaving the area if needed, applying an abrasive paste (SPES Medica, Italy) and finally cleaned with water.

2.5. Experimental procedure

Following placement of the reflective markers and sEMG electrodes, participants were seated with their arms crossed, and their hips and knees in 90° flexion. They were instructed to sit in a neutral position.

A feedback signal was created in LabView software (National Instruments, USA) which displayed an oscillating vertical gauge with real-time visualization of the actual trunk movement of the participant (Fig. 1). The real-time measure of the trunk motion was executed using the SMART ANALYZER suite (BTS Bioengineering, Milan, Italy) which was synchronized with the LabView software, in order to deliver the moving feedback gauge.

The task consisted of 12 continuous cycles of 50° trunk flexion and

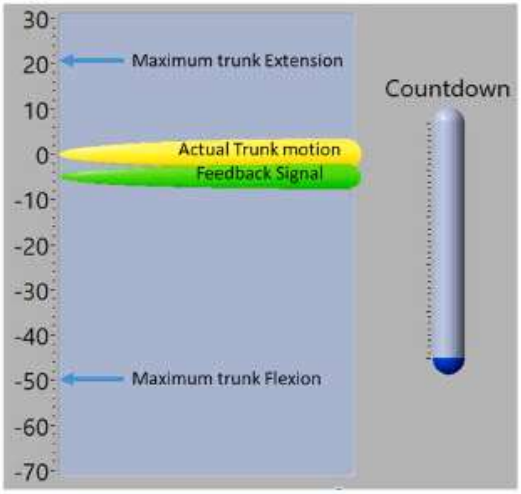


Fig. 1. Screenshot of the real-time feedback interface for the participants from the LabView software.

20° extension (full range) at two different speeds: 30°/s (slow) and 50°/s (fast) which were performed in a random order. Participants were instructed to move following the feedback into extension first to ensure better visualization of the screen followed by trunk flexion which was then repeated for 12 continuous cycles. The real-time visual feedback was provided using a large screen approximately 60 cm in front of the participant. The screen was positioned according to the subjects' height so that they were able to see it clearly and move comfortably. A maximum of three cycles of trunk flexion/extension were allowed as practice trials to familiarize participants with the task.

2.6. Signal processing

Using BTS SMART software suite (SMART Tracker; BTS Bioengineering, Italy), data from the reflective markers were tracked and labelled using a custom kinematic model for the trunk so any errors in the tracking were corrected. By creating a custom analysis protocol (SMART Analyzer), the tracked markers were interpolated and smoothed using a triangular window with a filter of 20 Hz to reconstruct any missing kinematic data. EMG signals were band-pass filtered with cut-off frequencies between 20 Hz and 400 Hz (2nd order Butterworth filter). These signals were then full-wave rectified and filtered again with a low-pass filter (2nd order Butterworth filter) with a cut-off frequency of 5 Hz. Normalization for the EMG data was conducted using a 300 ms mean of the rectified envelope signal during the resting condition just before the movement initiation when the velocity was zero [Martinez-Valdes et al., 2019, Martinez-Valdes, 2016].

In order to quantify motion of the spine, the SMART Analyzer protocol was used to create separate reference coordinate systems for each segment with three axes. The origin of the thoracic segment was set to be at a virtual point mid-way between the two markers at the level of T6 while for the lumbar segment was set from the marker at L3 to monitor movement of the mid-thoracic and lumbar spine (Fig. 2). In addition, a global reference system matching the laboratory orientation was used as a fixed reference system. The angular displacement of the mid-thoracic and lumbar segments were measured separately in degrees using Euler angles in relation to the fixed global reference system.

In order to evaluate the variability of tracking accuracy, the twelve continuous cycles of angular displacements were divided into 12 separate cycles and plotted against each other. Each cycle was time normalized to 101 samples (0–100% of cycle time). Point-by-point standard deviations (SD) were computed across all cycles then averaged to measure the mean of SD (MeanSD) (Fig. 3). This was calculated for each participant to quantify variability for lumbar and mid-thoracic spine motion [Asgari et al., 2015].

A custom made MATLAB code R2019a (The Mathworks, Natick, United States) was used to perform a cross correlation analysis in order to observe the similarity between the feedback signal and the actual trunk movement with the aim of detecting any temporal difference between the two signals in terms of e.g., anticipating or lagging relative to the feedback signal. The sample lag that was detected between the two signals was converted into time lag in seconds.

The normalized EMG signals were used to define a co-contraction index (CCI) between trunk flexors and extensors. The normalized EMG amplitude of lumbar erector spinae (nES) and obliques externus abdominis muscle (nOEA) were used in the following formula where ES was nominated as the agonistic muscle and OEA as the antagonistic [Kiewiet et al., 2017, Knarr et al., 2012]:

$$\text{Co} - \text{contraction Index}(\%) = 2 \times \left(\frac{\text{nOEA}}{\text{nOEA} + \text{nES}}\right) \times 100$$

A CCI of 100% indicates a comparable activation of the normalized antagonistic and agonistic EMG amplitude.

2.7. Statistical analysis

Normal distribution of the data was confirmed using a Shapiro–Wilk test. A Two-way Mixed Analysis of Variance (ANOVA) was conducted to detect any significant differences between the two groups in terms of temporal difference, variability of the tracking accuracy, and trunk muscle activation with between subject factor, group (control vs. LBP) and a within-subject factor, speed (slow vs. fast)

Pearson correlation was used to evaluate associations between the variability of tracking accuracy and EMG variables with questionnaires scores' for the LBP group including; ODI, FABQ-PA, FABQ-W, and VAS scores at the time of testing and over the past four weeks. SPSS Version 25 (IBM Corp., Armonk, NY, USA) was used for all statistical analyses and statistical significance was set at $P < 0.05$.

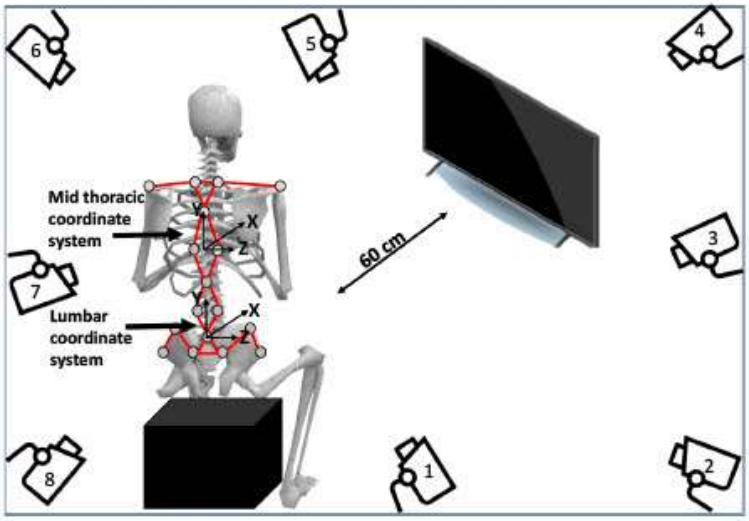


Fig. 2. The laboratory setup using 8 infrared cameras and 17 reflective markers with the coordinate system created for the mid-thoracic and lumbar regions.

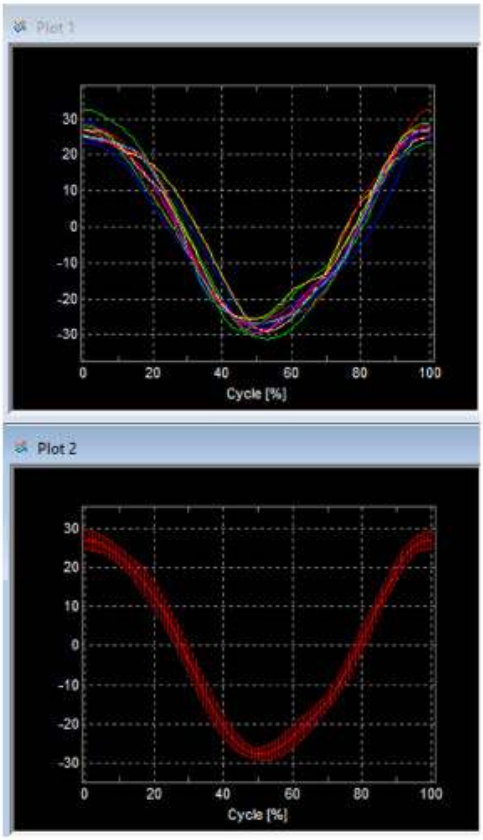


Fig. 3. Thoracic angular displacement displayed for one participant showing how the variability of the tracking accuracy was quantified. Plot1 illustrates the 12 cycles plotted against each other whereas Plot2 illustrates the point by point standard deviation and mean of the measured angular displacement for each cycle.

3. Results

Eleven asymptomatic volunteers and fifteen participants with LBP successfully completed data collection (Table 1). LBP group presented with minimal disability level and pain at the time of testing. There were no significant differences in the demographic characteristics between groups, with no differences identified in the mean age, height and body mass.

Table 1
Participant characteristics (mean ± SD).

	Asymptomatic (n = 11)	LBP (n = 15)	P-value
Age (years)	31.45 ± 4.25	37.06 ± 9.13	P = 0.072
Height (m)	1.70 ± 0.06	1.71 ± 0.05	P = 0.791
Body mass (kg)	66.00 ± 10.25	73.46 ± 8.60	P = 0.055
ODI (%)	–	10.8 ± 6.7	
Pain VAS	–	1.9 ± 2.1	
Average pain of the most recent episode	–	5.7 ± 2.1	
Actual Pain	–	2.1 ± 1.6	
Last 24 h Pain	–	2.3 ± 1.7	
Worst pain previous month	–	5.2 ± 2.7	
FABQ-W	–	9.1 ± 8	
FABQ-PA	–	13.5 ± 4.4	

3.1. Temporal difference between the feedback and actual trunk motion

The ANOVA revealed a significant main effect of group ($F(1, 24) = 15.9$, $P = 0.001$, $\eta p^2 = 0.399$) for the temporal difference. The control group were anticipating the feedback by 0.54 ± 0.55 s in the faster task and by 0.75 ± 0.78 s in the slower task whereas the LBP group anticipated the feedback in the faster task by 0.10 ± 0.54 s and in the slower task their motion was delayed relative to the feedback signal by 0.19 ± 0.32 s (Fig. 4). In contrast, there was no significant main effect of speed on the temporal difference ($F(1, 24) = 0.074$, $P = 0.787$, $\eta p^2 = 0.003$), with participants showing similar time lag or anticipation when performing the task at different speeds. In addition, there was no significant interaction effect between group and speed ($F(1, 24) = 3.50$, $P = 0.073$, $\eta p^2 = 0.127$).

3.2. Variability of the tracking accuracy

No significant main effect of group ($F(1, 24) = 1.90$, $p = 0.181$, $\eta p^2 = 0.073$) was observed for the tracking variability of the lumbar segment regardless of the movement speed ($F(1, 24) = 0.535$, $P = 0.472$, $\eta p^2 = 0.022$) (Fig. 5); the LBP group had similar tracking variability (fast speed = 3.61°±1.18°; slow speed = 4.17°±1.56°) compared to the control group (fast speed = 3.38°±1.02°; slow speed = 3.16°±1.14°). There was no significant interaction between group and speed ($F(1, 24) = 2.94$, $P = 0.099$, $\eta p^2 = 0.109$).

The tracking variability of the thoracic segment did not differ significantly between groups ($F(1, 24) = 0.382$, $P = 0.542$, $\eta p^2 = 0.016$). In contrast, there was a significant main effect of speed ($F(1, 24) = 4.15$, $P = 0.053$, $\eta p^2 = 0.148$) on the tracking variability of the thoracic segment (Fig. 5); therefore, the slower the task, the higher the tracking variability (slow task: control:4.77°; LBP:5.10°; fast task: control:4.36°; LBP:4.49°). However, there was no significant interaction between group and speed ($F(1, 24) = 1.69$, $P = 0.685$, $\eta p^2 = 0.007$).

A significant ($P = 0.03$; $r = 0.55$) moderate positive linear correlation was found between the tracking variability of the lumbar segment during the slow speed task and the FABQ-PA score (Fig. 6). A higher score on the FABQ-PA indicates more strongly held fear avoidance beliefs. This was not the case for the tracking variability of the lumbar segment during the fast speed task ($P = 0.08$; $r = 0.46$) nor for the thoracic spine segment during either the fast ($P = 0.149$;$r = 0.39$) or slow ($P = 0.366$;r

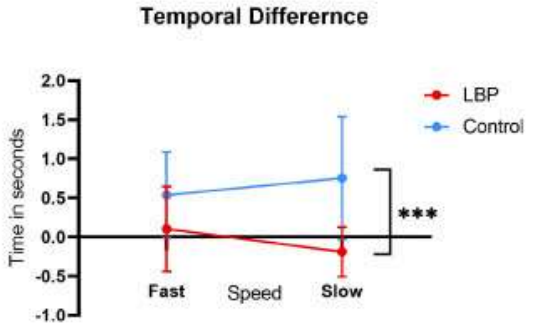


Fig. 4. Mean and SD of the temporal difference between the feedback signal and the actual trunk movement for asymptomatic people (controls) and people with low back pain (LBP). A positive value implies anticipation of the feedback signal whereas a negative value implies a delay relative to the feedback signal. ***:$p \leq 0.001$.

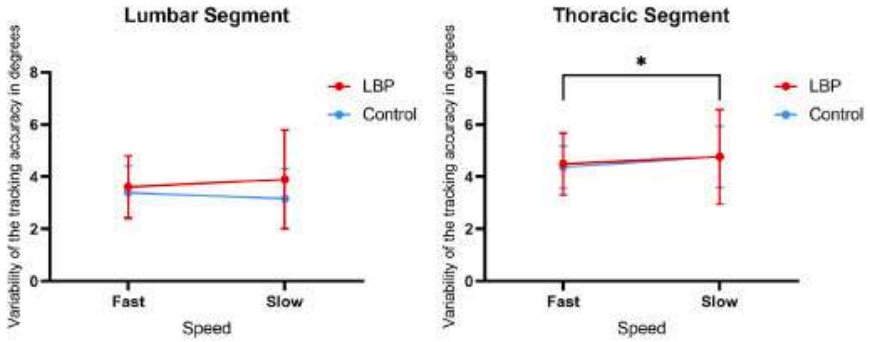


Fig. 5. Mean and SD of the variability of the tracking accuracy in asymptomatic people (controls) and people with low back pain (LBP). *: $p \leq 0.05$.

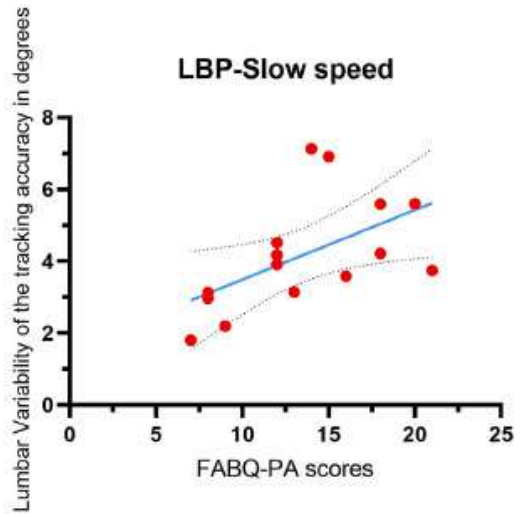


Fig. 6. The relationship between the variability of the tracking accuracy of the lumbar spine and the FABQ-PA scores.

= 0.25) speed tasks. Apart from this result there were no other significant correlations between the outcome measures and levels of pain and disability in the LBP group.

3.3. Muscle activity and co-contraction index

The CCI as well as the individual amplitude of ES and OEA activity did not differ significantly ($P > 0.05$) between LBP and asymptomatic groups in either task. However, there was a significant main effect of speed ($F(1, 24) = 15.8$, $P = 0.001$, $\eta p^2 = 0.397$) with greater OEA activity during the faster task in both groups (Table 2). Finally, there was no significant interaction effect between group and speed for muscle activity.

Table 2
Mean and SD of muscles activity and CCI for each group and task. ***:$p \leq 0.001$.

Group	Speed	Lumbar erector spinae (mV)	Obliques externus abdominis muscles (mV)	Co-contraction index CCI (%)
Control	Fast	1.40 ± 0.65	2.71 ± 1.51 ***	120.7 ± 21.8
	Slow	1.28 ± 0.53	1.88 ± 0.7 1	114.7 ± 20.6
LBP	Fast	1.40 ± 0.50	2.45 ± 0.85 ***	120.1 ± 16.8
	Slow	1.53 ± 1.10	1.96 ± 0.72	113.3 ± 21.0

4. Discussion

We evaluated trunk control using a novel 3D real-time tracking task that required precise trunk movements while varying the speed of motion. Asymptomatic people were able to anticipate the feedback signal when the task was performed at a slow or fast speed whereas the temporal difference between the feedback signal and the actual movement of the trunk was less in people with LBP and even became delayed when the task was performed at a slow speed (Fig. 4). Although, the variability of thoracic and lumbar motion didn't differ between groups over repeated cycles of the tracking task, the degree of lumbar motion variability during the slow speed task was significantly associated with the degree of fear of movement in those with LBP (Figs. 5 and 6). In contrast with our hypothesis, no difference in the degree of co-contraction of the trunk flexors and extensors was observed between groups.

Motor adaptation and learning are two fundamental processes for the flexibility of normal motor control [Bastian, 2008]. Although, both groups showed anticipatory motor adaptive behaviour at least during the faster movements, the response of those with LBP was delayed in comparison to the control group. A delayed motor behaviour in people with LBP has been attributed previously to slower initiation of motion at the pelvis resulting in greater delay at the onset of flexion when performing both functional and non-functional dynamic tasks [Claeys et al., 2012, Laird et al., 2019].

The repeated movements during slower task resulted in increased variability of tracking accuracy in both groups (Fig. 5). Previous studies also report reduced variability of thoracic and lumbar movement as the speed of motion increases [Asgari et al., 2015, Chehrehrazi et al., 2017], consistent with theory in motor control which describes how the temporal variability increases for slow movements when movements are constrained temporally [Plamondon, 1995].

The variability of tracking accuracy in the current study is considered to be a measure of spatial error, independent of timing error to test trunk precision control [Newell et al., 1994]. Therefore, it's more suitable to compare the current results to previous results on tracking error rather than movement variability. Our findings did not reveal greater error in those with LBP for the spatial parameters (i.e. RoM in degrees) when following the feedback. Previous studies have shown proprioceptive disturbances in people with LBP detected with 3D motion capture [Hidalgo et al., 2013, Sheeran et al., 2012], however these studies used repositioning error to quantify lumbar proprioceptive control.

Interestingly, a moderate linear correlation was found between the tracking variability of lumbar spine motion during the slow speed task and the FABQ-PA score (Fig. 6) which may indicate reduced ability of the participants with higher fear of movement to predict the parameters

needed to perform the underlying motor task [Schmidt, 2003]. Other reports indicate that people with LBP and high fear of movement tend to move slower and with a stiffer trunk [Karayannis et al., 2013, Osumi et al., 2019]. This may explain why the significant correlation between tracking accuracy and fear was only observed during the slow speed task. Other studies have reported weak correlations between increased repositioning error as a measure of accuracy and other self-reported outcomes such as pain intensity and disability [Åsell et al., 2006]. However, no significant correlations were reported in the present study between the variability of tracking accuracy and pain intensity or disability.

In the current study, we did not identify a difference in the level of trunk muscle co-contraction between groups, and although this has been observed in some studies investigating trunk muscle activity in LBP [e.g. van Dieën et al., 2003], there are also a number of studies which have not identified such differences [Arvanitidis et al., 2020, Martinez-Valdes et al., 2019, Mueller et al., 2017, Mueller et al., 2020]. Nevertheless, the difference in task performance implies different muscle activation and other features of the EMG signal (e.g. temporal and spatial features) could reveal differences between groups [Falla et al., 2014, Mueller et al., 2017, Sanderson et al., 2019]. Moreover, it is possible that the activity of other muscles, not recorded, differed between groups.

Although there was no effect of group on the activation pattern of the muscles, there was a significant effect of speed on the activation of the OEA muscle with higher activity at faster speeds, an observation confirmed previously [Vera-Garcia et al., 2008] which is possibly a strategy to stiffen the trunk as the task speed increases [Zoppirolli et al., 2017].

4.1. Methodological considerations

Instantaneous feedback of muscle activation intensity using EMG biofeedback has been commonly applied in research and clinical practice. In contrast, feedback on kinematics is less utilized likely due to the technical difficulties in assessing and quantifying these outcomes quickly and accurately [Hunt, 2013]. In the present study, we were able to provide such feedback despite these difficulties. A consideration is that the present study was limited to non-functional repeated trunk movements, which may not reflect actual dynamic activities of daily living. The participant sample size as well as the reported low levels of pain and disability may lack sensitivity to detect smaller effects. Thus, further studies with larger sample size and people with higher level of LBP is recommended for recruitment to improve generalisability of data.

5. Conclusion

In conclusion, people with LBP showed a delay relative to asymptomatic participants in tracking real-time feedback of trunk motion. Additionally, in those with LBP, the extent of the variability of lumbar spine motion was associated with the degree of fear of movement when the tracking task was performed at a slow speed. Collectively, this study provides new insights into how trunk control is modified in people with LBP.

Declaration of Competing Interest

None.

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Amal M. Alsubaie (PT, MSc) is a Lecturer at the Department of Physical Therapy, Faculty of Medical Rehabilitation Sciences at King Abdulaziz University, Jeddah, Saudi Arabia and a PhD student at the Centre of Precision Rehabilitation for Spinal Pain (CPR Spine) of the School of Sport, Exercise and Rehabilitation Sciences at the University of Birmingham, United Kingdom. She received her BSc in Physical Therapy (2012), King Abdulaziz University, Saudi Arabia and her MSc in Sport and Clinical Biomechanics (2016), Liverpool John Moores University, United Kingdom. Alsubaie Amal M. started her PhD at CPR Spine in 2019 supported by the Saudi Government to continue her higher education, with her main research focus on combining biomechanical and electrophysiological techniques to study human movement in people with and without low back pain.



Eduardo Martinez-Valdes (PT, MSc, PhD) is Lecturer (Assistant Professor) in Spinal and Musculoskeletal Physiotherapy at the Centre of Precision Rehabilitation for Spinal Pain (CPR spine) of the School of Sport, Exercise and Rehabilitation Sciences at the University of Birmingham, United Kingdom. He received both Master's and PhD degrees in Clinical Exercise Science from the University of Potsdam, Germany (2017). His PhD project was performed in collaboration with the Institute of Neurorehabilitation Systems at the University of Goettingen, Germany, where he received training in advanced surface electromyography processing techniques. Before being appointed as lecturer, Dr Martinez-Valdes worked as a postdoctoral research fellow at CPR spine in 2017-2018. Dr Martinez-Valdes research focuses on studying the neuromechanical processes underlying musculoskeletal pain, exercise and muscle fatigue. He is a member of the editorial board of the Journal of Electromyography and Kinesiology.



Dr De Nunzio is a leading expert in the field of Human Motion Analysis and Motor Outcome evaluation. He has extensive experience in research and clinics in Sensory-Motor Integration and Motor Rehabilitation. His main interest is Functional Biomechanics applied in Clinic. Dr De Nunzio received his Master Degree cum Laude in Biomedical Engineering from the University of Genoa, Italy, in 2002, the PhD degree in Physiological Sciences from the University of Pavia, Italy in 2006. He was the director of two Human Motion Analysis Laboratories (Salvatore Maugeri Foundation and NEUROMED IRCCS, Italy), and serving as Lecturer in Applied Biomechanics and Pain at the School of Sport, Exercise and Rehabilitation Sciences of the University of Birmingham (UK). He is leading the research activities of the LUNEX International University (Luxembourg) and heading the University Sport and Movement Lab as Associate Professor in Technology and Innovation in Health and Sport.



Professor Deborah Falla is Chair in Rehabilitation Science and Physiotherapy at the University of Birmingham, UK and is the Director of the Centre of Precision Rehabilitation for Spinal Pain (CPR Spine). Her research utilises state of the art electrophysiological measures to evaluate the control of human movement and how it is affected or adapted in response to various states (e.g. injury, fatigue, training and pain). She has published over 240 papers in international, peer-reviewed journals and more than 300 conference papers/abstracts including over 30 invited keynote lectures. She has received several recognitions and awards for her work including the German Pain Research Prize in 2014, the George J. Davies - James A. Gould Excellence in Clinical Inquiry Award in 2009 and the Delsys Prize for Electromyography Innovation in 2004. She is an author of three books including the latest entitled "Management of neck pain disorders: a research informed approach" (Elsevier, 2019). Professor Falla is an Associate Editor for Musculoskeletal Science & Practice, the Journal of Electromyography and Kinesiology and IEEE Transactions on Neural Systems and Rehabilitation Engineering. From 2016 to 2018, she was the President of the International Society of Electrophysiology and Kinesiology (ISEK).

Appendix 5 - Ethical Review, Consent form and Patient Information Sheets for *Chapter Three*

School of Sport, Exercise & Rehabilitation Sciences

Ethics Committee

Investigation of Human Subjects

Application Form

2017/18

1. Title of Project

Functional evaluation of trunk movements in people with low back pain

2. Investigators

Using the tables below, please list all involved including those from outside the School: also indicate their role in the project, either here or when outlining the protocol. If post-graduate students are involved in facilitating the project, please include them as staff.

Staff Investigators

Name	Role	Position	School/Institution
Alessandro Marco De Nunzio	Principal Investigator	Senior Research Fellow	Sport, Exercise and Rehabilitation Sciences
Deborah Falla	Co-investigator	Chair in Rehabilitation Science and Physiotherapy	Sport, Exercise and Rehabilitation Sciences
Bernard Liew	Co-investigator	Research Associate	Sport, Exercise and Rehabilitation Sciences

Student Investigators

Name	Role	Course	Registration period
Tejas Wagle	Investigator	773B - M.Sc. (Taught) Physiotherapy (pre-registration) Full-time	Until acad. yr. 2017-18
Andriana Tsiantoula	Investigator	774B - M.Sc. (Taught) MSc Advancing Physiotherapy Practice FT Full-time	Until acad. yr. 2017-18
Yik Lam Yvonne Szeto	Investigator	773B - M.Sc. (Taught) Physiotherapy (pre-registration) Full-time	Until acad. yr. 2017-18
Leung Chun Ting	Investigator	7214 - M.Sc. (Taught) Advanced Manipulative Physiotherapy Full-time	Until acad. yr. 2017-18
Aishwarya Bhatkhande	Investigator	773B - M.Sc. (Taught) Physiotherapy (pre-registration) Full-time	Until acad. yr. 2017-18

3. Purpose of the Research

Describe the purpose and background rationale for the proposed project, as well as the hypotheses/research questions to be examined and the expected outcomes. Please be concise, it is not necessary to provide extensive academic background material or references.

Low-back pain (LBP) is a highly prevalent and costly musculoskeletal pain syndrome, associated with recurrence and chronicity (Koes et al., 2006b). Approximately 75% to 85% of cases are classified as nonspecific chronic low back pain (NSLBP), with no detected evidence of pathoanatomical /radiological abnormality (Waddell, 2004).

Impairment in lumbar sensory-motor control is possibly a mechanism leading to the development and/or perpetuation of LBP. Impaired lumbar proprioception can decrease the ability to achieve and maintain a neutral spinal posture and appropriately coordinate muscle activation for control of trunk movement. Compromised spinal control can lead to increased spinal stresses and strain as a higher trunk muscle activity is generated, possibly prolonging LBP and causing further decay in proprioceptive abilities (Tong et al., 2017a).

The present study will investigate sensory-motor control of the lumbar spine in people with NSLBP by evaluating kinaesthetic control of the trunk using two different approaches:

- Joint repositioning sense (JRS) test with or without proprioceptive disturbance
- Analysis of the Helical Axis (HA) of the trunk motion across the different anatomical motion planes

JRS is the ability to relocate a target position of a body part without the aid of visual input and errors in executing the repositioning task have been correlated with proprioceptive impairment (Newcomer et al., 2000). The use of muscular vibration at the lumbar spine level, to induce proprioceptive disturbance, will test the effective contribution of muscle spindle afferences in repositioning. The role played by pain will be assessed trough comparison with a control group of healthy people.

The HA of joint motion has been proposed as a new approach to functionally analyse three-dimensional (3D) joint kinematics, as HA can vary depending on the irregularity of the joint surface and may be influenced by motor control (Barbero et al., 2017a).

4. Sample Characteristics

All relevant information about the nature of the target sample (age, sex, level of fitness etc.) should be provided, including the estimated sample size, and the inclusion/exclusion criteria to be applied. Please state clearly how participants will be identified, approached and recruited. Explain any relationship between the investigator(s) and the participant (e.g. instructor-student).

40 healthy and physically active participants & 40 participants who experience chronic NSLBP will be recruited.

Inclusion criteria:

- Both females and males are eligible for the study.
- The age range will be restricted to 18- 55 years to limit age effects on physical measures of the lumbar region.
- LBP and control participants must 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 by a GP, consultant or therapists (physiotherapist, osteopath, chiropractor) less than 3 months before enrolment.

5. Conduct of Project

a) Outline the research design to be adopted in the proposed study, including the overall duration of the project, where the study will take place and the time commitment for each participant. If the study involves more than one group then indicate how groups will be assigned.

Design: Observational case-control study

The project will start on January 2018 and end in July 2018.

The study will be conducted in the Movement Analysis Laboratory of the School of Sport, Exercise and Rehabilitation Sciences.

Participants will attend a single laboratory session which will last 90 min in total.

Healthy subjects will be recruited via poster advertisement and social media at the:

- School of Sport, Exercise and Rehabilitation Sciences (SportExR), College of Life and Environmental Sciences of the University of Birmingham
- Center for Pecision Rehabilitation of Spinal Pain (CPR Spine) of the SportExR School.

LBP participants will be recruited, via poster advertisement, from the community and population of staff and students at the University of Birmingham, and via social media at the CPR Spine and at the University level via the "Campus Announcements" web page.

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' (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.
The investigators' telephone and e-mail references will be provided on the 'Informed Consent' and 'Participant Information Leaflet'.
Each participating subject will receive a complete explanation of the study and its purpose following the measurements. A separate consent form will be signed by participants in case they will be willing to be part of the CPR Spine Register (attached).

b) Please provide a clear description of the study protocol and what the participants will experience, particularly if any discomfort is involved. If participants will be deceived in any way as part of the study, justification should be provided and a description of how the participants will be debriefed at the end of the study should be provided. For studies, which will involve a combination of different methodologies or interventions, it may be helpful to provide a timeline illustrating what each participant will experience.

The participants will undergo a kinematic evaluation of trunk motion with an infrared camera based optoelectronic system (BTS Bioengineering, Italy). Participants, starting from a neutral sitting position (on a stool, vertical alignment of trunk and head, feet height to assure 90 deg of flexion at knee joint) will be instructed to execute a series of trunk movements along the three anatomical planes (flexion/extension, lateral bending and axial rotation).
Two sub-sessions will be executed during the single laboratory session:

1. Joint Repositioning Sense (JRS) sub-session.

During JRS sub-session, the participant will be blindfolded and, starting from the neutral sitting position, will be instructed to execute a single trunk movement till reaching the limit of the corresponding range of motion (RoM: 90deg for trunk flexion, 30 deg for extension, 35 deg for lateral bending and 30 deg of trunk rotation). An auditory feedback of the reached RoM limit will be provided using the real time acquired data on trunk movements. As soon as the participant will reach the RoM limit he/she will be asked to reposition his/her

trunk to the neutral starting position. Three repetitions will be executed for each movement under 4 different "proprioceptive disturbance" conditions: i. no disturbance, ii. continuous disturbance, iii. Concentric disturbance, iv. Eccentric disturbance.

Proprioceptive disturbance will be provided using two muscular vibration units (Vibrasens VB115, Techno Concept, France) which will be positioned at 1st lumbar vertebra level, 4 cm from the spinous process. The vibrators will be strapped on the skin using two elastic therabands, which will assure constant contact with the skin without impeding trunk motion or creating any kind of discomfort.

The vibration units will deliver a 115 Hz mechanical vibration eliciting an afferent inflow mainly from Ia muscle spindles fibers from the muscles close to the vibration units (Roll and Vedel, 1982).

The vibration units will be i. turned off during the "no disturbance" condition, ii. turned on for the entire duration of the movement during the "continuous disturbance" condition, iii. Turned on just during the concentric phase of the lumbar paraspinal muscles activity (e.g. during extension or on the side of the lateral bending), iv. Turned on just during the eccentric phase of the lumbar paraspinal muscles activity (e.g. during flexion of the trunk).

A series of three repetitions per 6 different trunk movements (flexion, extension, right/left lateral bending, right/left rotation) per 4 different proprioceptive disturbance conditions will be realised for a total of 72 trunk movements. A software will assure randomisation across the different conditions.

Short resting periods (1-2 min) will be allowed every 10-15 min to avoid fatigue.

The main outcome of the JRS test will be the repositioning error calculated as the distance between the starting and ending position of the trunk for each of the executed movements.

2. Helical Axis (HA) sub-session.

During HA sub-sessions the participant, starting from the neutral sitting position, will be instructed to realise a series of continuous trunk movements under the following conditions:

- 10 continuous cycles of 70 deg flexion, 30 deg extension of the trunk,
- 10 continuous cycles of 35 deg flexion, 15 deg extension of the trunk,
- 10 continuous cycles of 35 deg left and right lateral bending of the trunk,
- 10 continuous cycles of 15 deg left and right lateral bending of the trunk,
- 10 continuous cycles of 30 deg left and right rotation of the trunk,
- 10 continuous cycles of 15 deg left and right rotation of the trunk.

The continuous cyclic movements will be realised at three different speeds: i. natural speed, ii. 40 bpm and iii. 20 bpm.

Real time visual feedback of trunk position will be provided, using TV glasses, to assure the participants will be able to cope with the prescribed RoMs during the 20 bpm and 10 bpm speed conditions. The TV glasses will not provide a virtual or augmented reality visual feedback but just a constant view of a 2D screen image displaying the actual trunk position and the reference position to follow.

During natural speed condition 2 repetitions of the continuous cyclic movements will be realised: i. with eyes open and, ii. with eyes closed. An auditory feedback will provide indication on reaching the prescribed degrees of motion under the "eyes closed condition".

During the HA sub-session a total of 6 cyclic continuous movements, per 3 different speeds, per 2 visual conditions (just during natural speed) will be executed, for a total of 24 movements. A software will assure randomisation across the different conditions.

Short resting periods (1-2 min) will be allowed every 10-15 min to avoid participant's fatigue.

The main outcome of the HA test will be the variability of the instantaneous rotation axes across the different cycles of each movement condition.

To assure a safe environment, an investigator will always be close to the participant for the entire session. This procedure will avoid any possible falls, which will be, in any case, highly unlikely.

Electomyographic (EMG) assessment

Surface EMG measurements will be acquired during the JRS and HA sub-sessions, synchronized with the kinematic 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:

- Latissimus Dorsi
- Lumbar Erector Spinae
- Rectus Abdominus
- Internal and External Obliques

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 which will be correlated with the main outcomes of the JRS and HA sub-sessions across the two different participants' groups.

Questionnaires data as described below will be obtained from the participants:

Healthy Controls - Self Reports

- SF-36 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 and Lovibond, 1995b)
- International Physical Activity Questionnaires (IPAQ) to measure physical activity of participants (Booth, 2000b)

LBP participants - Self Reports

- Numeric Rating Scale on Low Back Pain intensity and duration (with 0-10 as anchor points for no pain and the worst pain imaginable, respectively).
- International Physical Activity Questionnaires (IPAQ) to measure physical activity of participants (Booth, 2000b)
- SF-36 Health Survey: A measure of the general health status of the patient (Brazier et al., 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 and Lovibond, 1995b)
- The Oswestry Disability Index will be used to assess pain-related disability specifically related to LBP (7 items (Fairbank and Pynsent, 2000b))
- Fear Avoidance Believe Questionnaire (Waddell et al., 1993a)

Additionally, participants will report the area where the pain is felt by completing a pain drawing through sketch software on an iPad.

c) If a similar study protocol has already been approved by the School Ethics Committee then please provide the project title and ethics code and clearly indicate any changes to the present protocol.

NA

6. Data Management

a) Explain clearly whether data will be anonymous, or confidential, and the procedures in place to ensure anonymity/confidentiality. 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. Anonymity/confidentiality should be clearly explained in the participant information sheet. If participants will not be afforded anonymity/confidentiality, this should be fully justified and any risks addressed.

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 confidential to fully protect the privacy of the participating subjects.
Only PI and study supervisors 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. 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.

b) Data management strategies (including the retention of data) should comply with both the University's Code of Practice for Research (http://www.as.bham.ac.uk/legislation/docs/COP_Research.pdf) and the Data Protection Act 1998 (see http://www.legalservices.bham.ac.uk/dpa/ for further information). Therefore, for both hard copy and electronic data, please describe: what research data will be stored, where it will be stored and for what period of time, who will have access to the data and what measures will be in place to ensure data security.

~~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.

7. Risk Assessment

Any potential risks to individuals involved in the research study, and the measures put in place to minimise such risks should be documented in the form of a risk assessment. The risk assessment should then be submitted with this application.

Insignificant risks and risks from everyday life do not need to be included in the risk assessment unless your research procedures increase the normal level of risk. Therefore, if you feel that a risk assessment is not required for your project then please justify below.

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 standing up at the end of the measuring session or during rests. To assure a completely safe environment, an experimenter will be 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. The experimenter will check every 10-15 min possible dizziness manifestations administering a Visual Analog Scale (VAS) with two anchor points, 0 = no dizziness, 10 = unbearable dizziness. If the participant reports dizziness higher than 6 the session will be immediately stopped and the participant will be allowed to rest till complete disappearance of the symptoms.

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, the 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. flex the trunk to load the washing machine) 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 participant feels uncomfortable, the study session will be immediately stopped and the participant will be disengaged from the study.

A new risk assessment document may not be required if it is already available in the School Health and Safety folders (S:Safety). If this is the case then please state the risk assessment number below

NA

Further risk assessment guidance can be found on the Ethics Canvas page. Please contact Andy Benham (School Health and Safety Officer) if you require further information or assistance in completing your risk assessment.

8. Drugs and Diet

Are any drugs to be administered or will the diet be modified?

NA

9. Finance

Provide details of any outside sponsorship, either Research Council, charity or commercial organisation. If the study has been sponsored by an outside body have arrangements for insurance liability been discussed and agreed with the University's Legal and Insurance departments?

NA

10. Payment to participants

Detail all payments (or other inducements) to be made to subjects. Distinguish between reimbursement of expenses and payments for participation.

Participants will receive a fixed compensation of £10 for participating in the experiment.

In case of withdraw, participant will be offered compensation based on the time completed (fraction of the fixed amount based on the time spent at the laboratory for a maximum of £10 for 90 minutes).

11. Withdrawal

Include details of when the deadline for participant withdrawal will be, how this is communicated to participants, and if withdrawal has any implications for any payments indicated in section 10. The documentation to be given

to participants should clearly state whether they will be able to withdraw their data both during and after the study, and what they need to do in order to withdraw (e.g. who to contact). A reasonable time limit should be given for participant withdrawal (e.g., two weeks after the last day of data collection), as it is not usually possible for participants to withdraw once an analysis of their data has been included in material submitted for publication.

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 2 weeks following data collection without giving a reason.

12. Participant consent

Please tick the box if voluntary, written informed consent will be obtained from all participants. X

If written informed consent is not obtained from all participants, then explain below how consent will be obtained and provide appropriate justification.

NA

Copies of the participant information sheet and consent form should be submitted with your application. If verbal consent will be obtained, then include a sample 'script' of the information that participants will receive.

13. Planned start 01/01/2018 and end 30/07/2018 dates

I declare that the questions above have been ***answered truthfully*** and to the ***best of my knowledge*** and belief, and that ***I take full responsibility*** for these responses. I undertake to ***observe ethical principles throughout the research*** project and to report any changes that affect the ethics of the project to the School Ethical Review Committee for review. ***I have read and undertake to abide by*** the University's Code of Practice for Research (http://www.birmingham.ac.uk/Documents/university/legal/research.pdf).

Signature of project supervisor

Date: 07/12/2017

All applications must be submitted via the SportexR Ethics Canvas page

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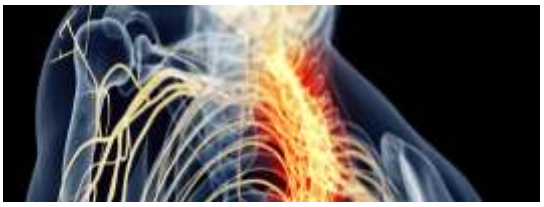
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Participant Information Sheet

Version 1

Date 07/12/2017

Study title

Functional evaluation of trunk movements in people with low back pain

Invitation paragraph

You are being invited to take part in a research study. Before you decide to participant 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 investigator or others if you wish.

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 trunk movements, which resemble activities of daily living (ADL) in presence of LBP (e.g. trunk flexion to load a dishwasher).

Why have I been chosen?

You have been chosen because we understand that you, as healthy and physically active subject could represent a normal reference in this study.

Other inclusion criteria include:

- age between 18 and 55 years

While exclusion criteria include:

- current or previous history of back or lower limb pain
- neuromuscular disorders
- musculoskeletal impairment.

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 2 weeks 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.

What will happen if I decide to take part?

You will be asked to visit the Movement Analysis Laboratory in the School of Sport, Exercise and Rehabilitation Sciences for approximately 90 minutes. During this time you will be asked to do the following

- Complete a series of questionnaires where eligibility will be confirmed.
- Perform a range of simple trunk movements during a sitting position. Resting periods will be frequently allowed to avoid any kind of discomfort or exhaustion.

What are the potential benefits and risks of taking part?

There is no immediate benefit to participate in this study. However the results of this project will increase our understanding of changes in sensory-motor control in response to LBP. This knowledge is relevant for the development and design of rehabilitation programs for individuals with LBP.

No risks have been foreseen in taking part to this study. A remote risk for dizziness onset during continuous trunk movement has been taken into account and frequently monitoring your dizziness sensation will represent the mitigation action to avoid any possibly induced discomfort. During the entire duration of the acquisition session, an investigator will be close to you to avoid any other balancing problems which are in any case unlikely to occur (for example a temporary unbalance can be felt standing up after completing the acquisition session as being sit for a long period of time).

Will my participation be confidential?

All information collected on you will be kept strictly confidential. Personal information will be retained, but only available to the researchers (contacts present at the end of this document) using password protected files. All data for presentation or publication in a research manuscript will be anonymised and aggregated, so your identity will not be revealed in any way.

What will happen at the end 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.

What if I have a problem or concern?

If you have a concern about any aspect of this study, please speak with Dr. Alessandro M De Nunzio.

Contact details are:

Email:

Phone:

Who has reviewed the study?

This study was reviewed by the Ethics Committee of School of Sport, Exercise and Rehabilitation Sciences at the University of Birmingham. You will receive a copy of the information sheet and of the signed consent form to keep.

Who is organizing and funding the study?

The study has been designed and organised by Dr. Alessandro M De Nunzio, Prof. Deborah Falla and supported by Dr. Nicola Heneghan and Dr Bernard Liew from the School of Sport, Exercise and Rehabilitation Sciences.

As a participant, you will be reimbursed a fixed amount of £10. In case of withdraw you will be offered compensation based on the time completed (fraction of the fixed amount based on the time spent at the laboratory for a maximum of £10 for 90 minutes).

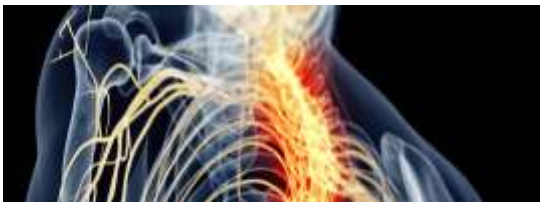
Contact for further information

Principal Investigator Dr. Alessandro M. De Nunzio Senior Research Fellow School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
Project co-investigator Prof. Deborah Falla Chair in Rehabilitation Science and Physiotherapy School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
Project co-investigator Dr. Bernard Liew Research Assistant School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
Investigator Tejas Wagle MSc student School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
Investigator Andriana Tsiantoula MSc student School of Sport, Exercise and Rehabilitation Sciences	

University of Birmingham	
Investigator Yik Lam Yvonne Szeto MSc student School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
Investigator Leung Chun Ting MSc student School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
Investigator Aishwarya Bhatkhande MSc student 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.

UNIVERSITY OF BIRMINGHAM | CENTRE OF PRECISION REHABILITATION FOR SPINAL PAIN



Participant Information Sheet

Version 1

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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 trunk movements, which resemble activities of daily living (ADL) in presence of LBP (e.g. trunk flexion to load a dishwasher).

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 experience pain on more than 90 days in the past 6 months

Other inclusion criteria include:

- age between 18 and 55 years

While exclusion criteria include:

- concurrent systemic, rheumatic or neuro-musculoskeletal disorders which may confound testing or 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 in the last year.

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 2 weeks 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.

What will happen if I decide to take part?

You will be asked to visit the Movement Analysis Laboratory in the School of Sport, Exercise and Rehabilitation Sciences for approximately 90 minutes. During this time you will be asked to do the following

- Complete a series of questionnaires where eligibility will be confirmed.
- Perform a range of simple trunk movements during a sitting position. Resting periods will be frequently allowed to avoid any kind of discomfort or exhaustion.

What are the potential benefits and risks of taking part?

There is no immediate benefit to participate in this study. However the results of this project will increase our understanding of changes in sensory-motor control in response to LBP. This knowledge is relevant for the development and design of rehabilitation programs for individuals with LBP.

No risks have been foreseen in taking part to this study. A remote risk for dizziness onset during continuous trunk movement has been taken into account and frequently monitoring your dizziness sensation will represent the mitigation action to avoid any possibly induced discomfort. During the entire duration of the acquisition session, an investigator will be close to you to avoid any other balancing problems which are in any case unlikely to occur (for example a temporary unbalance can be felt standing up after completing the acquisition session as being sit for a long period of time). In the unlikely event that your LBP will became worse, during the execution of the trunk movements, a longer resting period will be allowed. If rest will not mitigate the pain, the study will be immediately stopped.

Will my participation be confidential?

All information collected on you will be kept strictly confidential. Personal information will be retained, but only available to the researchers (contacts present at the end of this document) using password protected files. All data for presentation or publication in a research manuscript will be anonymised and aggregated, so your identity will not be revealed in any way.

What will happen at the end 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.

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Phone: [redacted]

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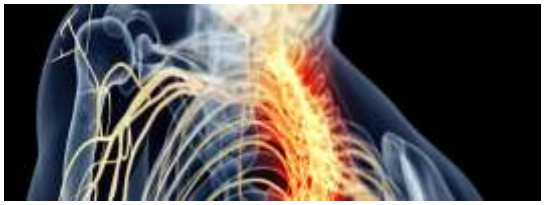
Contact for further information

Principal Investigator Dr. Alessandro M. De Nunzio Senior Research Fellow School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	[redacted]
Project co-investigator Prof. Deborah Falla Chair in Rehabilitation Science and Physiotherapy School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	[redacted]
Project co-investigator Dr. Bernard Liew Research Assistant School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	[redacted]
Investigator Tejas Wagle MSc student School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	[redacted]

Investigator Andriana Tsiantoula MSc student School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	
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Thank you for taking time to read this and considering taking part in the study.

UNIVERSITY OF BIRMINGHAM | CENTRE OF PRECISION REHABILITATION FOR SPINAL PAIN



PARTICIPANT CONSENT FORM

Study Title	**Functional evaluation of trunk movements in people with low back pain**		
Participant Name:		**Date:**	
Researcher Name:		**Ethics Number:**	

This section to be completed by the participant:

Please tick the box at the end of each statement if you agree with it.

1. I confirm that I have read and understood the Participant Information Sheet for the above study. I have had the opportunity to ask questions and these have all been answered satisfactorily	☐
2. I. understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, up to two weeks after my last visit to the lab.	☐
3. I agree to the storage and use of my data for the purposes of this research study.	☐
4. Based on the above, I agree to take part in this research study.	☐
Signed: Name in capitals: Date:	

This section to be completed by the researcher

I certify that this participant has read, properly completed and signed the screening and consent forms, witnessed by myself:

Signed:

Date:

By supplying this information you are consenting to the University storing your information for the purposes of the stated research study. 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.

Appendix 6 - Alsubaie et al. (2023b)

Journal of Electromyography and Kinesiology 73 (2023) 102832

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Spinal kinematic variability is increased in people with chronic low back pain during a repetitive lifting task

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ARTICLE INFO

Keywords:
Spine
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Lifting

ABSTRACT

Changes in spinal kinematic variability have been observed in people with chronic non-specific LBP (CNSLBP) during the performance of various repetitive functional tasks. However, the direction of these changes (i.e., less or more kinematic variability) is not consistent. This study aimed to assess differences in kinematic variability of the 3D angular displacement of thoracic and lumbar spinal segments in people with CNSLBP compared to asymptomatic individuals during a repetitive lifting task. Eleven people with CNSLBP and 11 asymptomatic volunteers performed 10 cycles of multi-planar lifting movements while spinal kinematics were recorded. For the three planes of motion, point-by-point standard deviations (SDs) were computed across all cycles of lifting and the average was calculated as a measure of kinematic variability for both segments. People with CNSLBP displayed higher thoracic ($F = 8.00$, $p = 0.010$, $\eta p^2 = 0.286$) and lumbar kinematic variability ($F = 5.48$, $p = 0.030$, $\eta p^2 = 0.215$) in the sagittal plane. Moreover, group differences were observed in the transversal plane for thoracic ($F = 7.62$, $p = 0.012$, $\eta p^2 = 0.276$) and lumbar kinematic variability ($F = 5.402$, $p = 0.031$, $\eta p^2 = 0.213$), as well as in the frontal plane for thoracic ($F = 7.27$, $p = 0.014$, $\eta p^2 = 0.267$) and lumbar kinematic variability ($F = 6.11$, $p = 0.022$, $\eta p^2 = 0.234$), all showing higher variability in those with CNSLBP. A significant main effect of group was not detected ($p > 0.05$) for spinal range of motion (ROM). Thus, people with CNSLBP completed the lifting task with the same ROM in all three planes of motion as observed for asymptomatic individuals, yet they performed the lifting task with higher spinal kinematic cycle-to-cycle variation.

1. Introduction

Low back pain (LBP) is one of the major leading causes of disability globally [Abrams et al, 2020, Hartvigsen et al, 2018]; chronic non-specific LBP (CNSLBP) accounts for the vast majority of cases [van Tulder et al, 2006]. Alterations in trunk movement patterns have been observed in people with LBP, however, the underlying mechanisms behind these motor control changes remains poorly understood [Hodges and Tucker, 2011, van Dieën et al, 2019]. Numerous studies have studied trunk movement patterns and trunk muscle activity in an attempt to understand strategies of trunk motor control in association with LBP [van Dieën et al, 2019]. One of the well-established strategies of motor adaptation to LBP are changes in spine kinematics, such as changes in trunk angular displacement, velocity, acceleration, as well as changes in the variability of these kinematic variables [Gizzi et al, 2019, Hodges and Smeets, 2015, Vaisy et al, 2015, van Dieën et al, 2017].

Kinematic variability is crucial when performing activities of daily living with high repeatability as well as in occupational settings [Abboud et al, 2014]. Repetitive lifting is one of the common functional tasks that has a reported causative role in LBP development and has frequently been investigated to better understand potential injury risks and strategies to improve lifting performance [Abdoli-Eramaki et al, 2019]. Yet, the majority of these studies explored lift-to-lift variability to understand the physical demands of the task in healthy individuals in

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order to optimise ergonomics [Oomen et al. (2023a); Oomen et al. (2023b), Tetteh and Mirka, 2018, Tetteh and Mirka, 2021]. The quantitative analysis of such inherent motor control variability during trunk repetitive movements was frequently driven from linear measures of spine kinematics such as range of motion, velocity or acceleration. Alterations in kinematic variability among people with LBP has also been observed as aberrant movement patterns when patients are asked to perform active trunk movements in different planes of motion during the physical examination [Biely et al, 2014, Gombatto et al, 2007, Marich et al, 2020]. These quantitative and qualitative analyses of kinematic features suggest inconsistent intra-individual movement variability when people with CNSLBP execute repetitive trunk movements [Dijk et al, 2021, Wattananon et al. (2023)].

A limited number of studies have explored kinematic variability during repetitive lifting in people with CNSLBP [Asgari et al, 2017, Bauer et al, 2015, Dideriksen et al, 2014, Fujii et al, 2022, Moreno Catalá et al, 2018, Pranata et al, 2018]. One study identified that the variability of lumbar movement patterns, in terms of angular displacement, was altered in those with greater LBP intensity as they performed a repetitive lifting task [Bauer et al, 2015]. However, most studies have explored coordination variability during repetitive lifting tasks in one plane of motion (trunk flexion and extension) and they have failed to identify different kinematic variability patterns in people with CNSLBP compared to asymptomatic individuals [Asgari et al, 2017, Fujii et al, 2022, Pranata et al, 2018].

The purpose of this study was to assess differences in kinematic variability of 3D angular displacement of two spine segments (thoracic and lumbar) in people with CNSLBP compared to asymptomatic individuals as they performed a cyclic lifting task performed in a multi-planar pattern. We hypothesised that people with CNSLBP would present with differences in motor control strategies revealed as a change in spinal kinematic variability given the more complex, multi-planar nature of the lifting task.

2. Methods

This was an observational study, conducted at the Centre of Precision Rehabilitation for Spinal Pain (CPR Spine) at the University of Birmingham. Ethical approval for the study was granted by the University Ethics Committee (Approval number: ERN_16-1389B), and the study was conducted according to the Declaration of Helsinki. All participants provided written informed consent. The study is reported in line with the STROBE guidelines [von Elm et al, 2008].

2.1. Participants

Twenty-two volunteers (men and women) aged 18–65 years were recruited from the student and staff community of the University of Birmingham, UK via poster and social media advertisements. Participants with CNSLBP were eligible if they had experienced LBP symptoms for more than three of the previous six month [Dionne et al. (2008)]. LBP participants were excluded if their pain was related to trauma, spinal stenosis, fractures, or if they experienced radiating leg pain. Age and BMI matched control participants were recruited and had to have no history of low back or lower limb pain which warranted attention from a healthcare practitioner. Participants from both groups were excluded if they were on high doses of anti-inflammatories (>30 mg morphine equivalent dose), pregnant, or were experiencing any concurrent systemic, rheumatic or neuro-musculoskeletal disorders which could confound testing.

2.2. Questionnaires

Baseline characteristics of participants were assessed by questionnaires prior to data collection. Anthropometric data were recorded at the beginning of the session. For the LBP participants, a bespoke back pain questionnaire was used to collect information on their LBP history and intensity which was assessed using a Pain Numeric Rating Scale (PNRS) [Breivik et al, 2008]. In addition, participants from both groups were required to complete several questionnaires including back disability assessed using the Oswestry Disability Index (ODI) [Fairbank and Pynsent (2000)], and their beliefs and fears about movement related to pain assessed by the Fear Avoidance Beliefs Questionnaire (FABQ) [Waddell et al, 1993]. Moreover, recent activity levels were assessed by the International Physical Activity Questionnaire (IPAQ) [Craig et al, 2003] and recent mental health by the Depression, Anxiety and Stress Scale (DASS-21) [Henry and Crawford, 2005, Lovibond and Lovibond, 1995]. General health at the time of data collection was assessed using the SF-36 (V2) [Walsh et al. (2003)]. Finally, the Borg Rating of Perceived Exertion (RPE) scale was used to measure the exertion rate after the performance of the lifting task [Borg, 1998].

2.3. Lifting task

The task consisted of a repetitive loaded lifting task between six shelves positioned in front and to the sides of the participant. In order to reduce the load on the low back during task performance, ergonomic interventions were applied individually for each participant by adjusting the location and height of each shelf based on their anthropometry [Faber et al, 2007]. Using adjustable shelves and palatable anatomical landmarks, the height and positions of shelves were determined (Fig. 1).

To reflect a task of lifting that may be encountered in daily living, the participants were asked to repetitively lift a standardised weight (5 kg) (35.5cm x 29cm x 13.5cm) in a multi-planar pattern of movement between the six shelves. The weight was standardized to ensure consistency and comparability among participants, while the choice of a 5 kg weight was based on it being considered manageable yet challenging enough to elicit physical exertion. To complete the task, participants 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]. From the standing position, participants performed 10 cycles of lifting. Specifically, the lifting task required the participant to move the box from the lower shelf-1 (S1) to a sequential shelf (e.g., S2), and then return to the starting position on S1, before moving to the next sequential shelf (i.e., S3, S4, S5, and S6), with rest between movements. Thus, S1 was identified as the start and the end of each lifting movement. For example, moving from S1 to S5 then back to S1 was defined as one complete lifting movement. In total, each participant completed 10 cycles of 5 lifting movements (i.e., S1-S2-S1,..., S1-S6-S1). In order to control the speed, the rhythm of the task was controlled by a metronome (30 beats per minute) with 2s allocated to each lifting movement followed by a rest of 2s. Participants were asked to not move their feet during lifting and to try to limit knee movement, but no further instructions were given regarding the lifting technique.

Before starting, the task was explained by researchers using standardised instructions, and a demonstration of one complete cycle was given. Participants were then allowed to practise one complete timed cycle with an unweighted box to ensure that the pattern and lifting technique at the knees and feet were performed as instructed. The task was completed in one continuous acquisition lasting approximately 7 min in total. Following task completion, participants were asked to rate their perceived effort using the RPE scale.

2.4. Motion capture

Three-dimensional movements of the trunk were captured using eight infrared cameras (BTS Bioengineering, Milan, Italy). The kinematic data was acquired at a frequency of 250 Hz following system calibration. A modified version of a previously described kinematic trunk model was used [Müller et al, 2016]. Ten reflective markers (14 mm) were placed with double-sided tape over the anatomical landmarks as illustrated in Fig. 2 in order to define two spinal segments. The

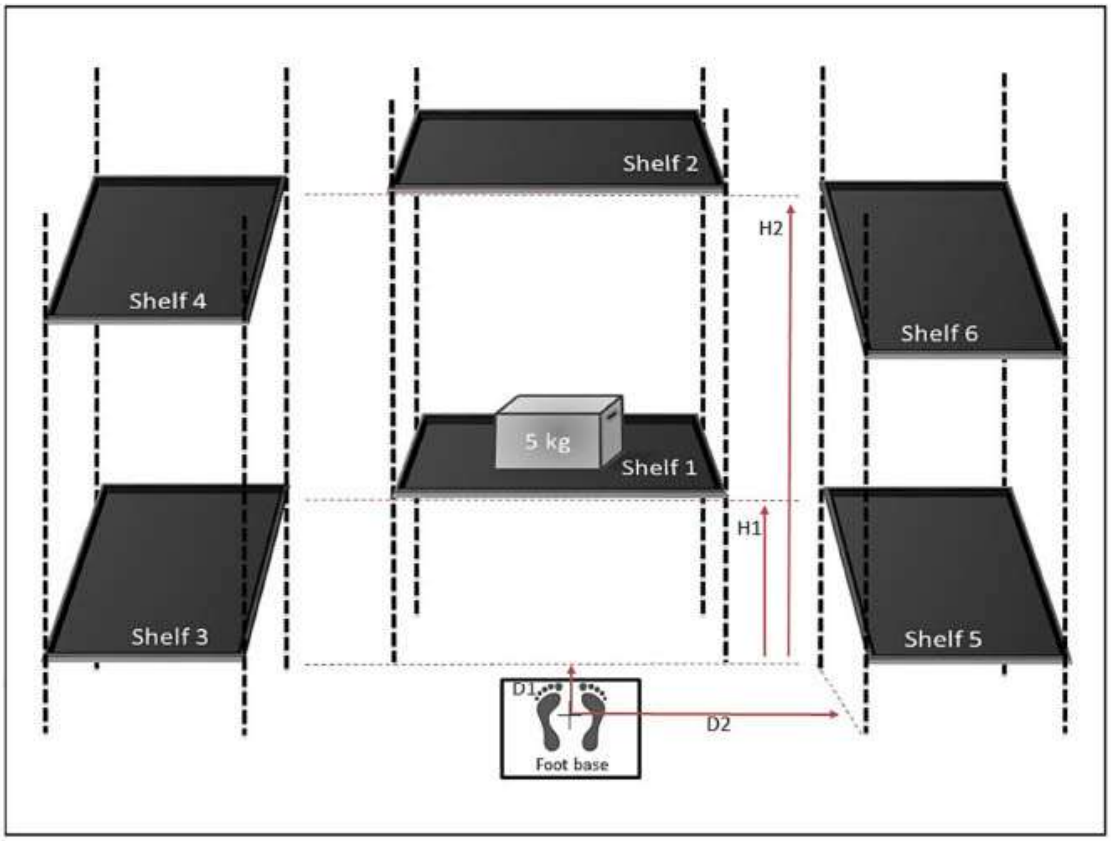


Fig. 1. Illustration of the experimental set-up showing the six adjustable shelves and the distance of the shelves from the foot-base which is located half-way between the two olecranon processes when the arms are abducted 90°. **D1**: the distance from acromion process to the ulnar styloid process when the arms are flexed 90°; **D2**: from the foot-base to the olecranon processes when the arms are abducted 90°. **H1**: the height of the lower shelves to the lateral femoral epicondyle height; **H2** the height of the upper shelves to manubriosternal angle height.

markers were placed in triangular patterns overlying the spine to facilitate division of the spinal regions into segments (Fig. 2). Reflective markers were also placed on the box, and the distal edge of each shelf (S1-S6).

2.5. Processing of 3D kinematic data

Using BTS SMART software suite (SMART Tracker& Analyzer; BTS Bioengineering, Italy), data from the reflective markers were tracked and labelled using a custom kinematic model for the trunk. Data were then processed using Matlab (R2022a, MathWorks, Natick, MA, USA). First, the 3D kinematic data obtained during the repetitive lifting task were interpolated and smoothed using a 2nd order Butterworth low-pass filter with a cut-off frequency of 5 Hz [Sanderson et al, 2019]. Then, the fifty continuous cycles (5 cycles × 10 times each) were divided into 50 separate trials using the markers positioned on the six shelves and the displacement of the marker placed on the box. Subsequently, each cycle was time-normalized to obtain 101 samples per cycle (0–100 % of cycle time) [Asgari et al, 2015].

The markers along the subject's spine were divided into a group of four markers in triangular patterns to define the two trunk segments (Fig. 2). The thoracic segment (TS) was defined by the markers on T12, T6 and 10 cm lateral to T6; the lumbar segment (LS) was defined by the markers on the S1, T12 and 10 cm lateral to T12. A Cartesian axis system was created for each trunk segment. In addition to the global coordinate system of the laboratory, a local coordinate system was defined at the pelvis level using three markers on the S1 and right and left iliac crest. Spinal angular displacement was expressed as the relative Euler angle of the movement of each spine segment with respect to the adjacent segment below, with the thoracic segment being relative to the lumbar segment and the lumbar segment relative to the pelvis. The three-dimensional rotation angles were calculated using an X-Z-Y (Frontal - Sagittal - Transverse) Cartesian sequence (Fig. 3) [Cotter et al, 2014, Needham et al, 2016, Preuss and Popovic, 2010].

To analyse the range of motion (ROM) during lifting movements, the angular displacement of each spinal segment has been measured as participants moved from the starting position (S1) to each subsequent shelf in three planes of motion in order to quantify the ROM achieved by each participant, even within the defined constraints of shelf positions and levels.

To quantify the kinematic variability of the spine angular displacement (thoracic, lumbar), point-by-point standard deviations (SDs) were computed across all 10 cycles for the five lifting movements in three planes of motions then averaged to measure the MeanSDs (Fig. 3) [Asgari et al, 2015].

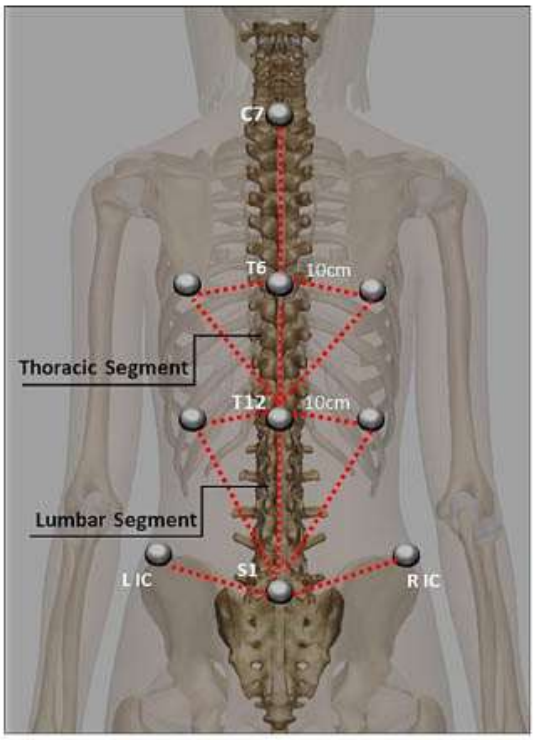


Fig. 2. Marker placement and segmentation for the spine kinematic model; the markers were adhered to the skin overlying 7th cervical vertebra (C7), 6th thoracic vertebra (T6), 12th thoracic vertebra (T12) and 1st sacral vertebra (S1), right iliac crest (R IC) and left iliac crest (L IC).

2.6. Statistical analysis

Normal distribution of the data was confirmed using a Shapiro–Wilk test and thus parametric tests were applied. Independent t-tests were used to compare differences in anthropometric data and clinical characteristics between groups. Separately for each plane of motion, two-way mixed Analysis of Variance (ANOVA) were conducted to compare main and interaction effects of group (control vs. CNSLBP; between subject factor), and shelves (S1-S2-S1,..., S1-S6-S1; within-subject factor) on thoracic and lumbar kinematic variability (MeanSDs). Whenever main effects were identified by ANOVA, Bonferroni post-hoc test was used for pairwise comparisons. The same analysis was also performed to assess spinal ROM (i.e., thoracic and lumbar angular displacement). Effect sizes were reported where appropriate with ANOVA results, in the form of ηp^2 values [Lakens, 2013]. Statistical analysis was performed using SPSS 29 (IBM, USA) with an alpha level set at $\alpha = 0.05$. All results are expressed as mean and standard deviation (Mean ± SD).

3. Results

Participants' characteristics are presented in Table 1. No significant anthropometric differences were found between groups for age or BMI ($P > 0.05$). The CNSLBP group reported mild current LBP intensity of 2.82/10 (±2.04), minimal disability level based on the ODI (15.59 ± 7.82 %) and reported moderate exertion during the task on the Borg scale (12.55 ± 1.80). As expected, those with CNSLBP presented with significantly higher degrees of back disability, fear of movement, and greater perceived exertion compared with asymptomatic individuals.

There was no significant main effect of group for the range of thoracic angular displacement in the sagittal plane while performing the lifting movement ($F = 1.34$, $p = 0.260$, $\eta p^2 = 0.063$). However, there was a main effect of shelf ($F = 13.83$, $p < 0.001$, $\eta p^2 = 0.40$), but no interaction effect between group and shelf ($F = 2.03$, $p = 0.140$, $\eta p^2 = 0.092$). In addition, there was also no significant main effect for group on the range of lumbar angular displacement in the sagittal plane ($F = 0.98$, $p = 0.332$, $\eta p^2 = 0.047$). Moreover, there was a main effect of shelf ($F = 18.84$, $p < 0.001$, $\eta p^2 = 0.40$), however, no interaction effect between group and shelf ($F = 0.19$, $p = 0.843$, $\eta p^2 = 0.009$).

In the transversal plane, there was no significant main effect of group on the range of thoracic angular displacement during the lifting movement ($F = 2.88$, $p = 0.105$, $\eta p^2 = 0.126$). However, there was again a main effect of shelf ($F = 8.14$, $p = 0.005$, $\eta p^2 = 0.28$), but no interaction effect between group and shelf ($F = 0.37$, $p = 0.594$, $\eta p^2 = 0.019$). In addition, there was no significant main effect of group on the range of lumbar angular displacement in the transversal plane during the lifting movement ($F = 0.74$, $p = 0.397$, $\eta p^2 = 0.036$). Moreover, there was no main effect of shelf ($F = 2.94$, $p = 0.064$, $\eta p^2 = 0.128$), nor interaction effect between group and shelf ($F = 2.13$, $p = 0.131$, $\eta p^2 = 0.097$).

In the frontal plane, there was no significant main effect of group on the range of thoracic angular displacement while performing the lifting movements ($F = 1.91$, $p = 0.182$, $\eta p^2 = 0.087$). There was also no main effect of shelf ($F = 1.85$, $p = 0.163$, $\eta p^2 = 0.085$) or an interaction effect between group and shelf ($F = 1.22$, $p = 0.307$, $\eta p^2 = 0.058$). Furthermore, there was no significant main effect of group on the range of lumbar angular displacement in the frontal plane during the lifting movement ($F = 3.27$, $p = 0.085$, $\eta p^2 = 0.141$). However, there was a main effect of shelf ($F = 13.4$, $p < 0.001$, $\eta p^2 = 0.401$); but no interaction effect between group and shelf ($F = 2.38$, $p = 0.093$, $\eta p^2 = 0.124$).

The range of angular displacement for each segment are presented in Table 2 in degrees of motion (°) and are expressed as Mean ± SD.

3.1. Differences in kinematic variability

3.1.1. Sagittal plane

For the thoracic segment, there was a significant main effect of group showing that people with CNSLBP displayed higher thoracic kinematic variability ($F = 8.00$, $p = 0.010$, $\eta p^2 = 0.286$) compared with healthy controls, independent of the five lifting movements. Thoracic kinematic variability for the CNSLBP group was 6.29°±0.70(SE), whereas for the healthy controls it was 3.48°±0.70(SE) with a mean difference of 2.81° and 95 % confidence interval (95 %CI) = 0.645, 2.23. In addition, there was a significant main effect for shelf ($F = 13.25$, $p < 0.001$, $\eta p^2 = 0.39$); thoracic kinematic variability was found to be higher for movements to the lower shelves (S3, S5) compared with the upper shelves (S4, 5, 6) (Bonferroni post-hoc results are shown in Table 3). Nevertheless, no interaction effect was observed between group and shelf ($F = 2.66$, $p = 0.095$, $\eta p^2 = 0.118$) (Fig. 4).

For the lumbar segment, there was a significant main effect for group and people with CNSLBP had greater lumbar kinematic variability ($F = 5.48$, $p = 0.030$, $\eta p^2 = 0.215$) compared with healthy controls, independent of the five lifting movements. Lumbar kinematic variability for the CNSLBP group was 5.69°±0.68(SE), whereas for the healthy controls it was 3.43° ±0.68(SE) with a mean difference of 2.25° and 95 %CI = 0.246, 4.267. There was a significant main effect of shelf ($F = 14.51$, $p < 0.001$, $\eta p^2 = 0.42$); lumbar kinematic variability was found to be higher for movements to the lower shelves (S3, S5) compared with the upper shelves (S4, 5, 6) (Bonferroni post-hoc results are shown in Table 3). However, no group by shelf interaction effect was observed for lumbar kinematic variability ($F = 1.10$, $p = 0.346$, $\eta p^2 = 0.052$) (Fig. 4).

3.1.2. Transverse plane

For thoracic segment, there was a significant main effect of group revealing that people with CNSLBP showed higher thoracic kinematic

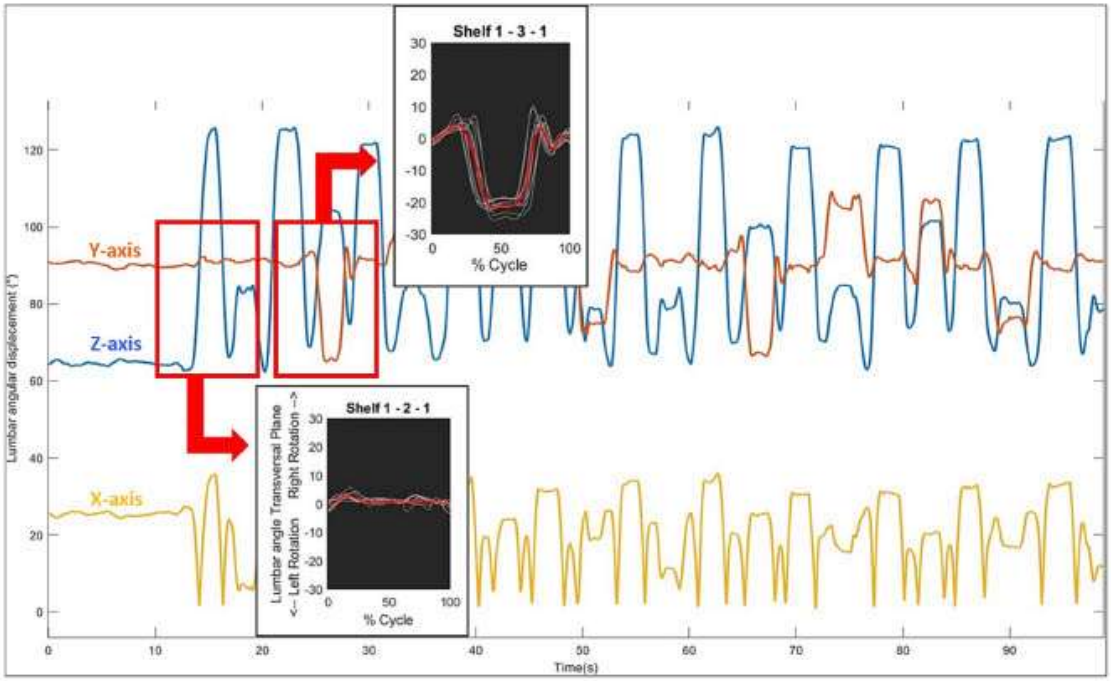


Fig. 3. An example outcome of lumbar angular displacements measured in three planes of motion (XYZ); (x-axis). Frontal, (z-axis): Sagittal, (y-axis): Transversal. Additionally, an example is presented of an extracted measure of kinematic variability as MeanSDs from the first and second lifting movement from transversal plane.

Table 1
Participant anthropometrics and questionnaires, data presented as Mean ± SD. **BMI:** body mass index, **IPAQ:** International Physical Activity Questionnaire, **ODI:** Oswestry Disability Index, **PNRS:** Pain Numeric Rating Scale, **FABQ:** Fear Avoidance Beliefs Questionnaire, **DASS-21:** Depression, Anxiety and Stress Scale, **RPE:** Borg Rating of Perceived Exertion, **CNSLBP:** chronic non-specific low back pain.

	Control group (N = 11; ♂: 4, ♀ 7)	CNSLBP group (N = 11; ♂: 5, ♀ 6)	P-value Two-sided
Age (years)	24.27 ± 4.62	25.82 ± 8.32	$P = 0.597$
BMI (kg/m²)	23.34 ± 4.71	25.17 ± 3.28	$P = 0.304$
IPAQ	83.33 % High	83.33 % High	–
SF-36 General Health	58.89 ± 2.04	49.38 ± 4.54	$P < 0.001$***
ODI (%)	0.36 ± 1.20 %	15.59 ± 7.82	$P < 0.001$***
Current PNRS	0	2.82 ± 2.04	$P < 0.001$***
Last 24hrs PNRS	0	3.82 ± 2.18	$P < 0.001$***
Average PNRS	0	5.32 ± 2.05	$P < 0.001$***
FABQ- total	1.91 ± 4.11	26.73 ± 11.55	$P < 0.001$***
DASS-21	9.82 ± 9.22	23.09 ± 28.83	$P = 0.161$
BORG (RPE) Scale	10.82 ± 1.83	12.55 ± 1.80	$P = 0.038$*

* $p < 0.05$; ** $p < 0.005$
*** $p < 0.001$.

variability ($F = 7.62$, $p = 0.012$, $\eta p^2 = 0.276$) compared with healthy controls. Thoracic kinematic variability for the CNSLBP group was 5.96° ±0.73(SE), whereas for the healthy controls it was 3.08° ±0.73(SE) with a mean difference of 2.87° and 95 %CI = 0.702, 5.043. Moreover, there was a significant main effect of shelf ($F = 22.41$, $p < 0.001$, $\eta p2 = 0.52$); thoracic kinematic variability was found to be higher for movements to the lower shelves (S3, S5) (Bonferroni post-hoc results are shown in Table 3). In addition, there was also an interaction effect observed between group and shelf, with only the CNSLBP group showing a significant change of thoracic kinematic variability with the lifting movements ($F = 5.60$, $p = 0.011$, $\eta p^2 = 0.219$) (Fig. 5).

For the lumbar segment, there was a significant main effect of group; people with CNSLBP displayed greater lumbar kinematic variability ($F = 5.402$, $p = 0.031$, $\eta p2 = 0.213$) compared with healthy controls, independent of the five lifting movements. Lumbar kinematic variability for the CNSLBP group was 5.28°±0.75(SE), whereas for the healthy controls it was 2.80°±0.75(SE) with a mean difference of 2.47° and 95 % CI = 0.254, 4.692. In addition, there was a significant main effect of shelf ($F = 14.67$, $p < 0.001$, $\eta p^2 = 0.42$); lumbar kinematic variability was found to be higher for movements to the lower shelves (S3, S5) (Bonferroni post-hoc results are shown in Table 3). However, no group by shelf interaction effect was observed for lumbar kinematic variability ($F = 2.12$, $p = 0.122$, $\eta p^2 = 0.096$) (Fig. 5).

3.1.3. Frontal plane

For the thoracic segment, there was a significant main effect for group revealing that people with CNSLBP showed higher thoracic kinematic variability ($F = 7.27$, $p = 0.014$, $\eta p^2 = 0.267$) compared with healthy controls. Thoracic kinematic variability for the CNSLBP group was 7.06°±0.79(SE), whereas for the healthy controls it was 4.03°±0.79 (SE) with a mean difference of 3.02° and 95 %CI = 0.686, 5.364. Moreover, there was a significant main effect of shelf ($F = 24.43$, $p < 0.001$, $\eta p^2 = 0.55$); thoracic kinematic variability was found to be higher for movements to the lower shelves (S3, S5) compared with the upper shelves (S4, 5, 6) (Bonferroni post-hoc results are shown in Table 3). In addition, there was also a group by shelf interaction effect ($F = 3.61$, $p = 0.049$, $\eta p^2 = 0.153$) (Fig. 6).

For the lumbar segment, there was a significant main effect of group; people with CNSLBP presented with greater lumbar kinematic

Table 2
Range of motion (ROM°) of thoracic and lumbar segments in three planes of motion while performing the lifting task.

Spinal segment: lifting movement	Group	ROM (°) Mean	SD
SAGITTAL PLANE			
TS: S1-2	Control	25.7076	23.79404
	CNSLBP	40.4448	30.34752
TS: S1-3	Control	35.2604	26.19830
	LBP	36.1412	22.00213
TS: S1-4	Control	24.6175	22.16953
	LBP	37.2505	28.97142
TS: S1-5	Control	9.6917	9.94578
	LBP	24.0107	22.65711
TS: S1-6	Control	27.6501	23.37993
	LBP	41.9509	30.28087
LS: S1-2	Control	24.1168	21.49180
	CNSLBP	34.1504	24.19698
LS: S1-3	Control	16.1412	12.86101
	LBP	23.8328	17.01420
LS: S1-4	Control	19.0390	17.03051
	LBP	26.8556	22.07910
LS: S1-5	Control	15.4389	14.54993
	LBP	22.7258	17.49828
LS: S1-6	Control	30.2190	23.26092
	LBP	36.9345	22.67231
TRANSVERSAL PLANE			
TS: S1-2	Control	0.9683	0.98345
	CNSLBP	2.0167	2.70154
TS: S1-3	Control	8.4676	7.15455
	LBP	17.5623	20.45796
TS: S1-4	Control	1.8536	1.73907
	LBP	3.3260	3.54669
TS: S1-5	Control	17.6183	20.53886
	LBP	20.1340	23.32670
TS: S1-6	Control	2.5131	1.51985
	LBP	4.9295	2.79128
LS: S1-2	Control	1.2955	1.17631
	CNSLBP	1.6796	1.75091
LS: S1-3	Control	2.8687	2.16165
	LBP	7.8367	8.59439
LS: S1-4	Control	8.7878	9.53290
	LBP	5.9735	9.55615
LS: S1-5	Control	8.5365	10.50324
	LBP	6.4309	4.31799
LS: S1-6	Control	2.7626	1.98506
	LBP	9.1921	9.77465
FRONTAL PLANE			
TS: S1-2	Control	1.4515	0.89976
	CNSLBP	0.3187	0.40559
TS: S1-3	Control	1.5263	1.00950
	LBP	1.6917	1.72632
TS: S1-4	Control	1.8074	1.36744
	LBP	1.5620	1.11343
TS: S1-5	Control	1.5833	1.31127
	LBP	1.4447	1.56585
TS: S1-6	Control	1.6872	1.45466
	LBP	0.9116	0.77797
LS: S1-2	Control	2.8065	1.74536
	CNSLBP	3.6037	2.85834
LS: S1-3	Control	1.9131	2.58310
	LBP	2.3729	2.77053
LS: S1-4	Control	4.5378	2.90925
	LBP	11.3994	9.29414
LS: S1-5	Control	1.1377	0.94547
	LBP	1.1069	1.46266
LS: S1-6	Control	5.3744	5.64915
	LBP	10.3013	8.82721

SD: Standard Deviation; TS: thoracic segment, LS: lumbar segment, S1-2: shelf1 to shelf2, CNSLBP: chronic non-specific low back pain.

variability ($F = 6.11$, $p = 0.022$, $\eta p^2 = 0.234$) compared with healthy controls and again this was independent of the five lifting movements. The lumbar kinematic variability for the CNSLBP group was 4.94°±0.43 (SE), whereas for the healthy controls it was 3.44°±0.43(SE) with a mean difference of 1.50° and 95 %CI = 0.236, 2.776. Further, there was a significant main effect of shelf ($F = 8.15$, $p < 0.001$, $\eta p^2 = 0.290$); lumbar kinematic variability was again found to be higher for movements to the lower shelves (S3, S5) (Bonferroni post-hoc results are shown in Table 3). However, no group by shelf interaction effect was observed for the measure of lumbar kinematic variability ($F = 2.24$, $p = 0.106$, $\eta p^2 = 0.101$) (Fig. 6).

4. Discussion

This study investigated the kinematic variability of spinal movement during repetitive lifting to test whether people with CNSLBP present with changes in trunk angular displacement variability as a potential motor adaptation to chronic pain. The results of this study showed no differences in thoracic nor lumbar ROM between asymptomatic individuals and people with CNSLBP when executing the repetitive loaded lifting task between six shelves arranged in a multi-planar manner. However, people with CNSLBP performed the task with significantly higher thoracic and lumbar kinematic variability between the ten cycles of lifting movements. This effect was observed for all five lifting movements in the sagittal, transverse and frontal planes of motion.

Recently, cross-sectional evidence demonstrated that people with LBP tend to lift with a slower and deeper squat with less spinal ROM compared to asymptomatic people [Nolan et al, 2020, Saraceni et al, 2021]. In the current study a similar ROM was observed for both groups, and this was expected given the standardization of the lifting task. The heights of the shelves which determined the ROM were individualized for each participant, therefore, no differences were expected or observed while executing the lifting movements [Matheve et al, 2019].

Interestingly, those with CNSLBP, despite performing the task with the same ROM as asymptomatic individuals, showed an altered strategy to execute the lifting task with higher cycle-to-cycle variation. Previous studies which have examined spinal kinematics during a repetitive lifting task have revealed that people with chronic LBP present with different movement control strategies when compared with asymptomatic individuals [Asgari et al, 2017, Bauer et al, 2015, Dideriksen et al, 2014, Fujii et al, 2022, Moreno Catalá et al, 2018, Pranata et al, 2018]. A more common observation in kinematic variability is an increase in kinematic variation in the sagittal plane of motion when picking up a box from the floor [Bauer et al, 2015]. The same finding was observed in the current study albeit while performing a more complex multi-planar lifting task.

There are several possible explanations for the increased spinal kinematic variability observed for those with CNSLBP, for example, it may reflect an attempt to avoid aggravating pain or an attempt to minimise back muscle fatigue. The relationship between motor variability and fatigue has been explored previously based on the variability in muscle activation [Falla et al, 2014, Farina et al, 2008], which revealed that higher variability can lead to longer endurance and reduced development of fatigue in healthy volunteers [Farina et al, 2008]. In contrast, people with LBP have reduced variability of back muscle activity during repetitive lifting tasks and this is thought to contribute to pain provocation during task performance [Falla et al, 2014]. In the current study however, people with CNSLBP presented with greater perceived exertion despite higher kinematic variability.

While pain and fatigue are considered potential explanations for the higher kinematic variability in CNSLBP people, other research proposes that changes in spinal kinematics may be influenced by psychological pain-related factors, such as fear of movement [Fujii et al, 2022, Fujii et al, 2021]. Although those with CNSLBP that were recruited in the current study presented with higher levels of fear of movement compared with asymptomatic individuals, the limited number of participants in our study prevented us from examining any potential associations between clinical and kinematic variables.

Table 8
Results of Bonferroni post hoc multiple comparisons for shelf effect on the thoracic and lumbar kinematic variability in all planes of motions.

Shelf- Shelf:Mean (°)			Mean Difference	Std. Error	Sig.	95 % Confidence Interval for Difference	
						Lower Bound	Upper Bound
SAGITTAL PLANE							
Thoracic Kinematic variability							
S2 (4.005)	S3	6.053	−2.049*	0.614	0.033	−3.984	-0.113
	S4	3.864	0.141	0.224	1.000	-0.565	0.846
	S5	6.905	−2.900*	0.812	0.019	−5.459	-0.340
	S6	3.639	0.365	0.299	1.000	-0.577	1.308
S3 (6.053)	S2	4.005	2.049*	0.614	0.033	0.113	3.984
	S4	3.864	2.189**	0.563	0.009	0.413	3.966
	S5	6.905	-0.851	0.381	0.371	−2.053	0.350
	S6	3.639	2.414**	0.619	0.009	0.461	4.368
S4 (3.864)	S2	4.005	-0.141	0.224	1.000	-0.846	0.565
	S3	6.053	−2.189**	0.563	0.009	−3.966	-0.413
	S5	6.905	−3.041**	0.751	0.006	−5.408	-0.674
	S6	3.639	0.225	0.412	1.000	−1.075	1.525
S5 (6.905)	S2	4.005	2.900*	0.812	0.019	0.340	5.459
	S3	6.053	0.851	0.381	0.371	-0.350	2.053
	S4	3.864	3.041**	0.751	0.006	0.674	5.408
	S6	3.639	3.265**	0.755	0.003	0.884	5.647
S6 (3.639)	S2	4.005	-0.365	0.299	1.000	−1.308	0.577
	S3	6.053	−2.414**	0.619	0.009	−4.368	-0.461
	S4	3.864	-0.225	0.412	1.000	−1.525	1.075
	S5	6.905	−3.265**	0.755	0.003	−5.647	-0.884
Lumbar Kinematic variability							
S2 (3.941)	S3	4.798	-0.857*	0.245	0.022	−1.629	-0.085
	S4	4.103	-0.162	0.165	1.000	-0.682	0.357
	S5	5.890	−1.950**	0.428	0.002	−3.298	-0.601
	S6	4.077	-0.137	0.211	1.000	-0.803	0.529
S3 (4.798)	S2	3.941	0.857*	0.245	0.022	0.085	1.629
	S4	4.103	0.695**	0.204	0.028	0.051	1.338
	S5	5.890	−1.092	0.373	0.082	−2.267	0.082
	S6	4.077	0.720	0.332	0.424	-0.327	1.768
S4 (4.103)	S2	3.941	0.162	0.165	1.000	-0.357	0.682
	S3	4.798	-0.695*	0.204	0.028	−1.338	-0.051
	S5	5.890	−1.787***	0.333	<0.001	−2.837	-0.738
	S6	4.077	0.025	0.215	1.000	-0.651	0.702
S5 (5.890)	S2	3.941	1.950**	0.428	0.002	0.601	3.298
	S3	4.798	1.092	0.373	0.082	-0.082	2.267
	S4	4.103	1.787***	0.333	<0.001	0.738	2.837
	S6	4.077	1.813*	0.389	0.002	0.586	3.039
S6 (4.077)	S2	3.941	0.137	0.211	1.000	-0.529	0.803
	S3	4.798	-0.720	0.332	0.424	−1.768	0.327
	S4	4.103	-0.025	0.215	1.000	-0.702	0.651
	S5	5.890	−1.813**	0.389	0.002	−3.039	-0.586
TRANSVERSAL PLANE							
Thoracic Kinematic variability							
S2 (2.775)	S3	7.202	−4.427***	0.785	<0.001	−6.903	−1.951
	S4	3.780	−1.005**	0.300	0.032	−1.951	-0.059
	S5	6.236	−3.461***	0.642	<0.001	−5.486	−1.437
	S6	2.627	0.148	0.396	1.000	−1.098	1.393
S3 (7.202)	S2	2.775	4.427***	0.785	<0.001	1.951	6.903
	S4	3.780	3.422***	0.662	<0.001	1.334	5.510
	S5	6.236	0.965	0.429	0.358	-0.387	2.318
	S6	2.627	4.575***	0.925	<0.001	1.657	7.492
S4 (3.780)	S2	2.775	1.005**	0.300	0.032	0.059	1.951
	S3	7.202	−3.422***	0.662	<0.001	−5.510	−1.334
	S5	6.236	−2.456**	0.602	0.006	−4.353	-0.559
	S6	2.627	1.153	0.400	0.092	-0.108	2.413
S5 (6.236)	S2	2.775	3.461***	0.642	<0.001	1.437	5.486
	S3	7.202	-0.965	0.429	0.358	−2.318	0.387
	S4	3.780	2.456**	0.602	0.006	0.559	4.353
	S6	2.627	3.609**	0.767	0.001	1.190	6.028
S6 (2.627)	S2	2.775	-0.148	0.396	1.000	−1.393	1.098
	S3	7.202	−4.575***	0.925	<0.001	−7.492	−1.657
	S4	3.780	−1.153	0.400	0.092	−2.413	0.108
	S5	6.236	−3.609**	0.767	0.001	−6.028	−1.190
Lumbar Kinematic variability							
S2 (2.495)	S3	5.586	−3.091***	0.592	<0.001	−4.957	−1.225
	S4	4.054	−1.559***	0.314	<0.001	−2.550	-0.568
	S5	4.542	−2.046**	0.495	0.005	−3.608	-0.485
	S6	3.538	−1.043	0.366	0.099	−2.198	0.112
S3 (5.586)	S2	2.495	3.091***	0.592	<0.001	1.225	4.957
	S4	4.054	1.532	0.517	0.077	-0.097	3.161
	S5	4.542	1.045	0.378	0.119	-0.147	2.236

(continued on next page)

Table 8 (continued)

SAGITTAL PLANE Thoracic Kinematic variability Shelf- Shelf:Mean (°)			Mean Difference	Std. Error	Sig.	95 % Confidence Interval for Difference Lower Bound	 Upper Bound
	S6	3.538	2.048**	0.490	0.005	0.503	3.593
S4 (4.054)	S2	2.495	1.559***	0.314	<0.001	0.568	2.550
	S3	5.586	−1.532	0.517	0.077	−3.161	0.097
	S5	4.542	-0.487	0.343	1.000	−1.568	0.594
	S6	3.538	0.516	0.349	1.000	-0.583	1.615
S5 (4.542)	S2	2.495	2.046**	0.495	0.005	0.485	3.608
	S3	5.586	−1.045	0.378	0.119	−2.236	0.147
	S4	4.054	0.487	0.343	1.000	-0.594	1.568
	S6	3.538	1.003*	0.288	0.023	0.097	1.910
S6 (3.538)	S2	2.495	1.043	0.366	0.099	-0.112	2.198
	S3	5.586	−2.048**	0.490	0.005	−3.593	-0.503
	S4	4.054	-0.516	0.349	1.000	−1.615	0.583
	S5	4.542	−1.003*	0.288	0.023	−1.910	-0.097
FRONTAL PLANE							
Thoracic Kinematic variability							
S2 (4.320)	S3	7.773	−3.453***	0.683	<0.001	−5.606	−1.301
	S4	4.353	-0.033	0.334	1.000	−1.086	1.019
	S5	7.820	−3.500**	0.771	0.002	−5.931	−1.069
	S6	3.474	0.846**	0.215	0.008	0.167	1.524
S3 (7.773)	S2	4.320	3.453***	0.683	<0.001	1.301	5.606
	S4	4.353	3.420***	0.559	<0.001	1.658	5.181
	S5	7.820	-0.047	0.362	1.000	−1.189	1.095
	S6	3.474	4.299***	0.731	<0.001	1.995	6.603
S4 (4.353)	S2	4.320	0.033	0.334	1.000	−1.019	1.086
	S3	7.773	−3.420***	0.559	<0.001	−5.181	−1.658
	S5	7.820	−3.467***	0.657	<0.001	−5.538	−1.396
	S6	3.474	0.879	0.445	0.621	-0.524	2.282
S5 (7.820)	S2	4.320	3.500**	0.771	0.002	1.069	5.931
	S3	7.773	0.047	0.362	1.000	−1.095	1.189
	S4	4.353	3.467***	0.657	<0.001	1.396	5.538
	S6	3.474	4.346***	0.852	<0.001	1.659	7.033
S6 (3.474)	S2	4.320	-0.846*	0.215	0.008	−1.524	-0.167
	S3	7.773	−4.299***	0.731	<0.001	−6.603	−1.995
	S4	4.353	-0.879	0.445	0.621	−2.282	0.524
	S5	7.820	−4.346***	0.852	<0.001	−7.033	−1.659
Lumbar Kinematic variability							
S2 (3.953)	S3	4.720	-0.767**	0.195	0.008	−1.380	-0.153
	S4	4.157	-0.204	0.319	1.000	−1.209	0.801
	S5	4.660	-0.707*	0.220	0.043	−1.399	-0.014
	S6	3.478	0.474	0.200	0.275	-0.155	1.104
S3 (4.720)	S2	3.953	0.767**	0.195	0.008	0.153	1.380
	S4	4.157	0.563	0.254	0.385	-0.238	1.364
	S5	4.660	0.060	0.130	1.000	-0.351	0.471
	S6	3.478	1.241***	0.249	<0.001	0.456	2.027
S4 (4.157)	S2	3.953	0.204	0.319	1.000	-0.801	1.209
	S3	4.720	-0.563	0.254	0.385	−1.364	0.238
	S5	4.660	-0.503	0.287	0.954	−1.409	0.403
	S6	3.478	0.678	0.371	0.822	-0.491	1.847
S5 (4.660)	S2	3.953	0.707*	0.220	0.043	0.014	1.399
	S3	4.720	-0.060	0.130	1.000	-0.471	0.351
	S4	4.157	0.503	0.287	0.954	-0.403	1.409
	S6	3.478	1.181**	0.248	0.001	0.399	1.963
S6 (3.478)	S2	3.953	-0.474	0.200	0.275	−1.104	0.155
	S3	4.720	−1.241***	0.249	<0.001	−2.027	-0.456
	S4	4.157	-0.678	0.371	0.822	−1.847	0.491
	S5	4.660	−1.181**	0.248	0.001	−1.963	-0.399

* $p < 0.05$.
** $p < 0.005$.
*** $p < 0.001$.

4.1. Methodological considerations

Certain limitations of this study need to be acknowledged. Firstly, we included a relatively a small sample size and this prevented us from investigating any potential correlations between kinematic variability and pain-related factors. Nevertheless, we were still able to determine significant differences in spinal kinematic variability between groups. Despite the modest mean differences in kinematic variability of around three degrees, the effect sizes ranged from moderate to large. Nevertheless, it remains unclear whether this is a clinically meaningful difference. However, this study provides new insights into motor adaptations to CNSLBP, which may lead to targeted interventions that can potentially improve the management of individuals with CNSLBP.

4.2. Conclusion

People with CNSLBP completed a standardised repetitive lifting task with the same spinal ROM as asymptomatic individuals, yet with a different motor strategy to execute the lifting task which was characterised by higher kinematic cycle-to-cycle variation.

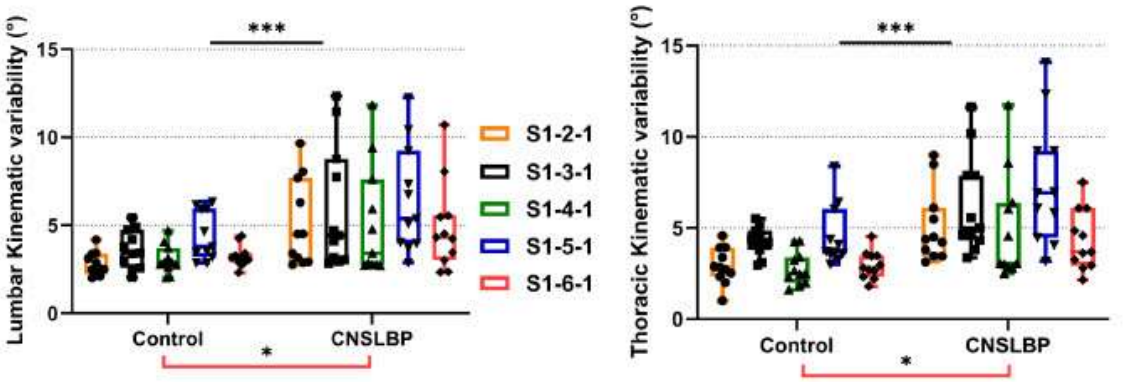


Fig. 4. Thoracic and lumbar kinematic variability differences between people with chronic non-specific low back pain (CNSLBP) and healthy controls in the Sagittal plane of motion, data presented as mean and standard deviation; S1-2–1: shelf1 to shelf2 to shelf1. The lower line represent the statistically significant main effect of group, the upper line represent the statistically significant main effect of shelf: *$p < 0.05$; **$p < 0.005$; *** $p < 0.001$.

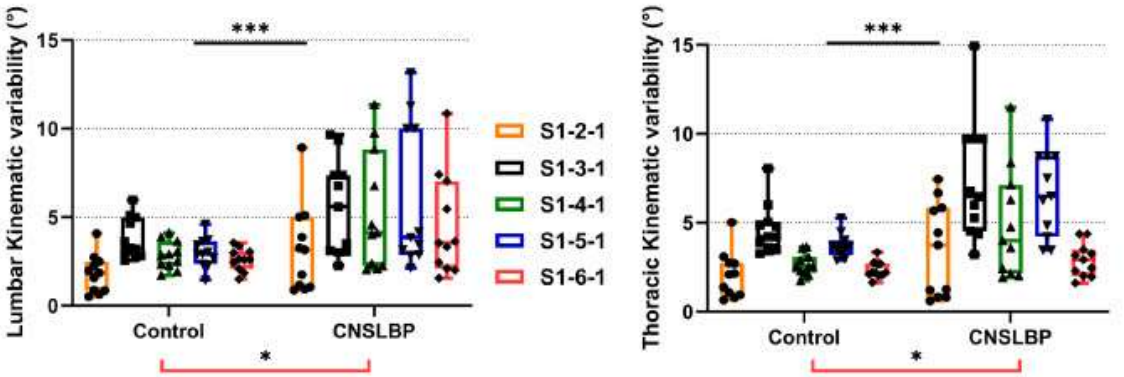


Fig. 5. Thoracic and lumbar kinematic variability differences between people with chronic non-specific low back pain (CNSLBP) and healthy controls in the Transversal plane of motion, data presented as mean and standard deviation; S1-2–1: shelf1 to shelf2 to shelf1. The lower line represent the statistically significant main effect of group, the upper line represent the statistically significant main effect of shelf: *$p < 0.05$; **$p < 0.005$; *** $p < 0.001$.

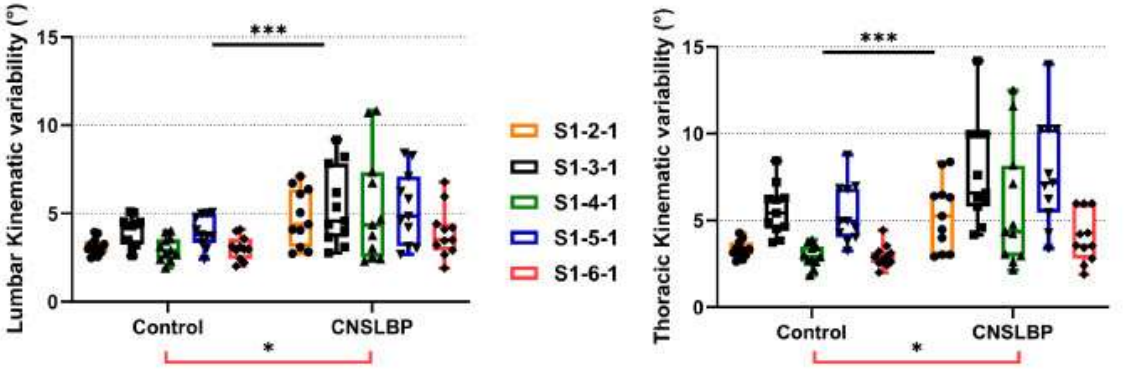


Fig. 6. Thoracic and lumbar kinematic variability differences between people with chronic non-specific low back pain (CNSLBP) and healthy controls in the Frontal plane of motion, data presented as mean and standard deviation; S1-2–1: shelf1 to shelf2 to shelf1. The lower line represent the statistically significant main effect of group, the upper line represent the statistically significant main effect of shelf: *$p < 0.05$; **$p < 0.005$; *** $p < 0.001$.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 7 - Ethical Review, Ethical Amendments, Consent Forms and Patient Information Sheets for *Chapter Four*

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
Telephone:	
Email address:	

Name: Title / first name / family	Dr. Alessandro Marco De Nunzio
Highest qualification & position held:	Research Fellow
School/Department	School of Sport, Exercise and Rehabilitation
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
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
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
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			

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 (Vos et al., 2012, Hong et al., 2013, Kalichman et al., 2010, Parsons and Courtney, 2014). Many studies in this field have been performed under static conditions which do not represent patients' daily-life routines (Mazaheri et al., 2013, Gallagher and Callaghan, 2016, Gallagher and Callaghan, 2015). 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 et al., 2006, Schweigart and 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 et al., 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 (Winter et al., 1998, Morasso and Schieppati, 1999) will induce variation in gravitational moments around the spine that have to be controlled by trunk musculature to maintain trunk alignment (Creath et al., 2005, Hodges et al., 2002, Oullier et al., 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 (Schieppati et al., 1994, De Nunzio et al., 2005, Courtine et al., 2007, De Nunzio et al., 2008, Mientjes and Frank, 1999).

Niels and Sinnott in 1991 (Nies and 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 et al., 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 (Schieppati and Nardone, 1999, Roll et al., 1989b, Kavounoudias et al., 1998, Kavounoudias et al., 1999) and jointly contribute to the body schema formation (Roll et al., 1989b). Tendon vibration almost selectively activates muscle spindle primary endings and elicits a discharge in the fast conducting large-diameter group Ia afferent fibers (Roll and Vedel, 1982, Roll et al., 1989a) 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 et al., 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 (Schieppati et al., 1994, McCollum and Leen, 1989). 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 and McGill, 1996, Panjabi, 1992b), 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 et al., 2005, Park et al., 2004).

A well-studied example of APAs occurs during the transition from stationary standing to stepping forward to initiate gait (Crenna and Frigo, 1991, Rogers et al., 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.

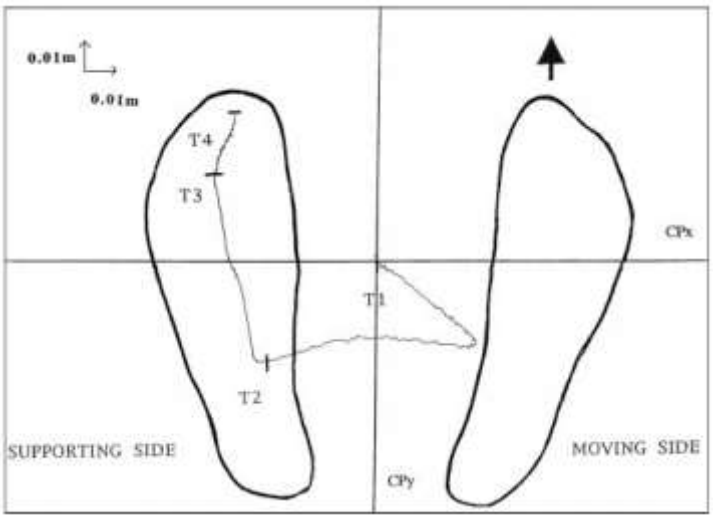


Figure 1 - adapted from Viton et al. 2000

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 and Drew, 2003, Schepens and Drew, 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 et al., 2004, Matsuyama and 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 et al., 1999, Massion et al., 2004). 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 and 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 (Stenhagen et al., 2013, Gryfe et al., 1977).

Sudden stopping is accomplished in a single step, always with one foot forward (leading leg) and the other back (trailing leg) (Sparrow and 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 and Stein, 1998, O'Kane et al., 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 (Oates et al., 2010, O'Kane et al., 2003). 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 (Ivanenko et al., 2006, Sousa and Tavares, 2015, Barker et al., 2006, Coutts, 1999). 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 (Labruyere and van Hedel, 2012, Domenici et al., 1998), thereby resulting in the production of smooth, adapted trajectories (Hase and Stein, 1999). Constraints of equilibrium, already present during straight-ahead locomotion (Pozzo et al., 1998, Cavagna and Margaria, 1966), also challenge the CNS during curved walking (Guglielmetti et al., 2009, Thigpen et al., 2000, Godi et al., 2010).

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 and Schieppati, 2003b, Courtine and Schieppati, 2003a). 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 et al., 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 and Schieppati, 2003a, Courtine and Schieppati, 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 et al., 2006, Courtine and 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 (Schmid et al., 2005, Courtine et al., 2007), 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 and 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 and 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 et al., 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 and Sanguineti, 2002, Morasso and 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. (Davis et al., 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 (Perotto, 1994, Hermens et al., 1999). 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 et al., 2008), (Falla et al., 2014a).

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 (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 (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 (Davis et al., 1991)

- pelvis rotation (deg),
- hip rotation (deg),
- knee rotation (deg),
- ankle rotation (deg),

- elevation angles for right and left side (Borghese et al., 1996, Lacquaniti et al., 1999, Ivanenko et al., 2008b)

- 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 et al., 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 et al., 2002, Kolenda et al., 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 (Patla, 1985, Davis and Vaughan, 1993, Olree and Vaughan, 1995, Ivanenko et al., 2004, Ivanenko et al., 2005, Ivanenko et al., 2008a, Cappellini et al., 2006, Clark et al., 2010, McGowan et al., 2010, Gizzi et al., 2011).

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 et al., 2008a)), 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., 2014a) 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 (Borghese et al., 1996, Bianchi et al., 1998), 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, Lacquaniti et al., 1999, Ivanenko et al., 2008b). 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 et al., 2006a) 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 and Lovibond, 1995b)
- International Physical Activity Questionnaires (IPAQ) to measure physical activity of participants (Booth, 2000b)

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, 2000b)
- 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 et al., 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 and Lovibond, 1995b)
- The Oswestry Disability Index will be used to assess pain-related disability specifically related to LBP (7 items (Fairbank and Pynsent, 2000b))
- Fear Avoidance Believe Questionnaire (Waddell et al., 1993a)

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 et al., 2016)
- Tinetti Performance Oriented Mobility Assessment (POMA) (Thomas and Lane, 2005, Sterke et al., 2010)
- Activities-specific Balance Confidence (ABC) Scale (Lajoie and 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 (Hubscher et al., 2014, Blumenstiel et al., 2011, O'Neill et al., 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 <u>first registered as from 1st September 2008</u> 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**

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
Telephone:	
Email address:	

Name: Title / first name / family	Dr. Alessandro Marco De Nunzio
Highest qualification & position held:	Research Fellow
School/Department	School of Sport, Exercise and Rehabilitation
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
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
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	Deborah Falla		

Name of student:	Pauline Kuithan	Student No:	
Course of study:	PhD	Email	
Principal	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**	**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**

	participants were recruited and methodology)		**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	**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

	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**		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.

Methods

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

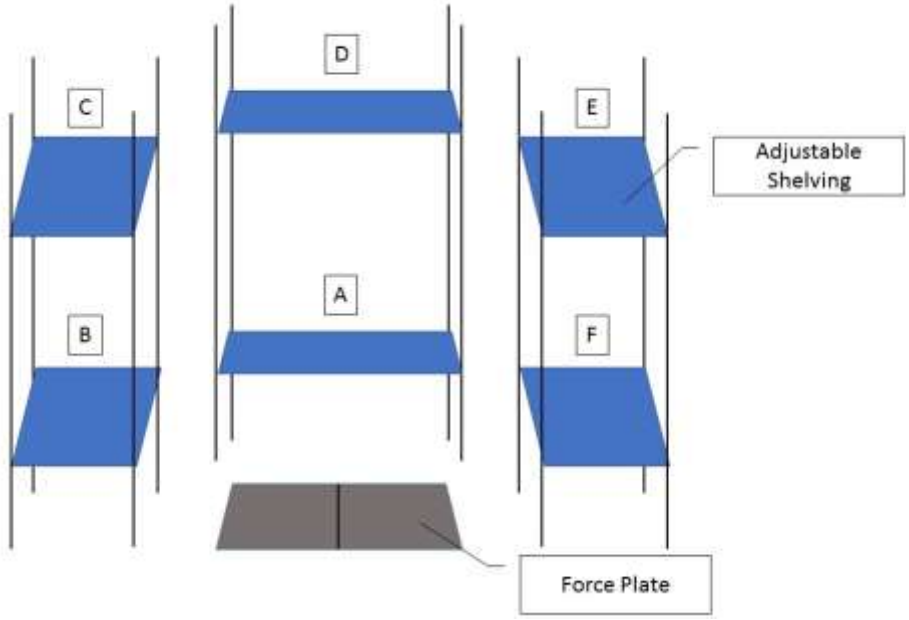


Figure 1 –Experimental set-up with adjustable shelving and a force plate

(**Figure 1**).

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. (2014a). 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., 2014a). 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., 2014a). 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., 2006b, O' Conaire et al., 2011, Falla et al., 2014a). 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., 2014a). 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., 2014a). 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., 2014a).

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., 2014a, Koes et al., 2006b, 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., 2014a, 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.

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,

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……..

Contact details of participant

Contact number:

Email address:

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	[redacted]
Project co-investigator Dr. Alessandro M. De Nunzio Senior Research Fellow School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	[redacted]
Project co-investigator Dr. Alison Rushton Senior Lecturer School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	[redacted]
Project co-investigator Dr. Nicola Heneghan Lecturer School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	[redacted]
PhD Student Andy Sanderson School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	[redacted]
PhD Student Pauline Kuithan School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	[redacted]

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.

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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	[redacted]

Project co-investigator Dr. Alessandro M. De Nunzio Senior Research Fellow School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	[redacted]
Project co-investigator Dr. Alison Rushton Senior Lecturer School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	[redacted]
Project co-investigator Dr. Nicola Heneghan Lecturer School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	[redacted]
PhD Student Andy Sanderson School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	[redacted]
PhD Student Pauline Kuithan School of Sport, Exercise and Rehabilitation Sciences University of Birmingham	[redacted]

Thank you for taking time to read this and considering taking part in the study.

Appendix 8 - Ethical Review, Ethical Amendments, Consent Forms, Patient Information Sheets and Recruitment posters for *Chapters Five and 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

Investigating trunk motor variability during repetitive movements 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

g) 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	Sports, Exercise, and Rehabilitation Sciences
Telephone:	
Email address:	

h) 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 in Spinal and Musculoskeletal
School/Department	Sports, Exercise, and Rehabilitation Sciences
Telephone:	
Email address:	

i) In the case of PGR student projects, please give details of the student

Name of	Amal Alsubaie	Student	
Course of study:	PhD sport, exercise and rehabilitation	Email address:	
Principal supervisor:	Professor Deborah Falla		

4. ESTIMATED START OF PROJECT Date: January 2020

ESTIMATED END OF PROJECT Date: January 2021

5. FUNDING

List the funding sources (including internal sources) and give the status of each source.

Funding Body	Approved/Pending /To be submitted
Saudi Arabia Government Scholarship	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.

Background rationale

The socioeconomic burden of low back pain (LBP) is increasing rapidly despite technological advances in diagnosis and intervention (Dagenais et al., 2008, Key, 2010). One of the main reasons for individuals with LBP to seek medical help is due to limitation in function (Mortimer and Ahlberg, 2003). This is commonly noted during the year preceding the assessment of the problem in the form of reduced physical performance at work (Ratzon et al., 2007). In addition, individuals with LBP have also reported issues with routine functioning and activities of daily living (Grabovac and Dorner, 2019). In the presence of LBP, people are expected to move differently than pain-free individuals as an inherited adaptive behaviour (Hodges and Tucker, 2011a). Furthermore, a narrative review by (Grabovac and Dorner, 2019) showed that LBP is commonly followed by a level of kinesophobia, which leads patients to avoid certain movements and activities**.** On the other hand, an assumption has been made by the kinesiopathological (KP) model that the musculoskeletal pain develops as a result of the repeated usage of specific patterns of movements and postures throughout the day (Marich et al., 2017).

The high level of repeatability in the activities of daily living as well as in occupational settings shows the importance of motor variability. Motor variability reflects a wide range of motor solutions available in order to prevent, delay or alleviate muscle fatigue and potential musculoskeletal disorders and injuries (Abboud et al., 2014b). Different methods have been developed recently in order to measure and interpret variability using different types of variables including kinetic components that focus on forces or kinematic components that focus on position, velocities and acceleration of the movement pattern as well as muscle activity and recruitment patterns (Srinivasan and Mathiassen, 2012b). There is preliminary evidence suggesting differences in motor variability between healthy individuals and patients with chronic musculoskeletal disorders (Abboud et al., 2014b).

The helical axis (HA) of motion is one of the recently proposed approaches to functionally investigate three-dimensional joint kinematics since joint movements usually involve rotation of one body segment relative to another (Barbero et al., 2017b). However, the axis of rotation of one segment in relation to another are not usually fixed, but vary in orientation and position due to the different shapes of joint surfaces and the variability of muscle activation. The HA method allow to estimate this unique orientation and position for each axis of motion that will be created with each cycle of motion (Dugailly et al., 2015b). To date there has been no attempt to describe HA of trunk during a movement without the need of a 3D reconstruction of the bones of the joint. Therefore, the aim of the study is to describe the dispersion of HA parameters in people with and without CNSLBP.

Purpose:

To examine the variability of trunk movement in healthy asymptomatic controls and people with CNSLPB by measuring changes in the parameters of HA during three repetitive uniplanar movements (i.e. trunk flexion /extension, right/left rotation, right/left lateral bending) as well as to observe the differences of muscle activity and recruitment patterns of the trunk muscles. This will be done in two different experiments:

- To test the effects of changing speed by asking participants to repeat the tasks at three different speed levels **(Experiment 1)**
  To test the effect of fatigue by asking the participants to perform the tasks before and after a lumber endurance task **(Experiment 2)**

Expected outcomes:

We hypothesise that CNSLPB individuals will present with significantly less variable movement and a more rigid trunk when preforming the repetitive movement particularly during faster speeds and in fatigued conditions.

7. CONDUCT OF PROJECT

Please give a description of the research methodology that will be used

Design

Experiment 1&2: Observational case-control studies

Setting

The project will take place in the School of Sport, Exercise and Rehabilitation Sciences, University of Birmingham and all measurements will be collected within the laboratories of the Centre of Precision Rehabilitation for Spinal Pain (CPR Spine).

General procedures

Anthropometric data (i.e. age, height, weight) will be collected at the beginning of each experiment.
At the beginning of each experiment, the CNSLBP group will report the current level of pain (at the time of testing) and pain intensity level over the prior week and month of testing by using a pain numeric rating scale PNRS (0-10). They will also complete an electronic pain drawing followed by these questionnaires:

- International Physical Activity Questionnaires (IPAQ) to measure physical activity of participants (Booth, 2000b)
- SF-36 Health Survey: A measure of the general health status of the patient (Brazier et al., 1992)
- The Oswestry Disability Index (ODI) will be used to assess pain-related disability specifically related to LBP (7 items) (Fairbank and Pynsent, 2000b) (CNSLBP group only)
- Fear Avoidance Belief Questionnaire (Waddell et al., 1993a) (CNSLBP group only)
- Depression, Anxiety, Stress Scales (DASS): A self-rating measure of depression, anxiety and stress (Lovibond and Lovibond, 1995b)

Only the IPAQ will be completed by the asymptomatic participants.

These questionnaires are widely used in research and in clinical practice, while their evaluations have shown that they have good psychometric properties and hence are able to assess what they were designed to (Jenkinson et al., 1994; Craig et al., 2003; Swinkels-Meewisse et al., 2003; Lee et al., 2017).

The three-dimensional movements of the trunk will be captured using an optoelectronic system (BTS Bioengineering, Milan, Italy) while preforming 30 repetitive uniplanar trunk movements (i.e. flexion/extension, right/left rotation, and right/left lateral bending). Simultaneously, the activity of the trunk muscles (abdominal, back and side muscles) will be recorded bilaterally using synchronized wireless Electromyography (EMG) probes (FREEEMG, BTS Bioengineering, Milan, Italy). The full experiment time for each experiment will last approximately two hours.

For Experiment 1: Each uniplanar trunk movement will be performed in three conditions: at a natural self-selected speed, slow (30 beat /min) speed and fast (50 beat/min) speed.

For Experiment 2: Each uniplanar trunk movement will be performed in the three previously mentioned speed conditions before and after preforming a lumber endurance task to induce fatigue.

From both experiments, the parameters of the helical axis HA (mean distance MD, and mean angle MA) will be measured between three proposed segments of the trunk (whole thoracic, upper lumber, and lower lumber). Which will give an insight about the thoraco-lumber variability as well as the upper-lower lumber variability of movement. In term of muscles' activity, an index will be measured to look at the simultaneous co-activation or the co-contraction of the abdominal and back muscles as well as both sides' muscles.

In addition, for (**Experiment 2)** the rate of perceived exertion (RPE) will be recorded at 15-second intervals and immediately following task failure using the Borg RPE scale. This measure will be used to assess the perceived exertion of the participants throughout the task and ensure that the task is appropriate for CNSLBP participants. The participants will be also timed using a stopwatch to record their endurance time.

From the previously mentioned measurements, the following outcome measures will be compared between CNSLBP participants and asymptomatic controls:

- Based on the HA analysis: mean distance (MD), and mean angle (MA) of each axis across the different anatomical motion planes.
- Changes in the muscles co-contraction indexes.
- Correlations between HA parameters and levels of pain, disability, fear of movement, and physical activity in the participants with CNSLBP
- Level of pain (PNRS, 0-10).
- Rate of perceived exertion (RPE) using the Borg scale (RPE scale,6-20)(Experiment 2 only)
- Endurance time in seconds (Experiment 2 only)

Statistical analysis

Descriptive statistics will be used to interpret the data and it will be presented as mean ± SD. If the criteria are met, two way analysis of variance (ANOVA) will be used. A combination of different factors, group (CNSLBP, controls) and conditions (speed of motion) will be appropriately used to analyse each variable. For experiment 2, repeated measures ANOVA will be used with one within-subject factor (pre vs. post-fatiguing task) and one between-subject factor (CNSLBP vs. control). T-tests will be also performed when appropriate. If data is not normally distributed, relevant nonparametric tests will be used.

Specific Procedures

Experimental set-up

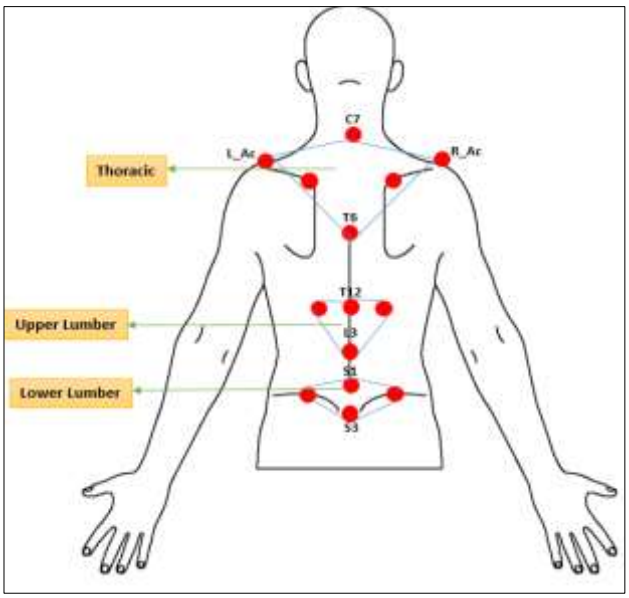
Participant preparation:

Marker placement:

For both experiments, the three-dimensional movements of the trunk will be captured using eight infrared cameras (BTS Bioengineering, Milan, Italy) with a resolution of 2,2 Mpixels (2048×1088 pxs).This is in order to track 14 spherical retroreflective markers (14mm) attached on the skin along the subject's spine. The kinematic data will be acquired at a frequency of 125 Hz following system calibration. A modified version of (Preuss and Popovic, 2010) kinematic trunk model will be used. The marker placement **(Figure 1)** will define three spinal segments: whole thoracic, upper lumber, and lower lumber segment.

Thee participant will be asked to sit and expose the back in order to place the markers with a double sided tape on the anatomical landmarks illustrated in Figure 1.

Figure 1: Marker placement and spine segmentation for the kinematic model of spine motion.



EMG probes placement:

Surface EMG measurements will be acquired during both experiments, synchronized with the kinematic 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). Wireless Bipolar Ag-AgCl surface electrodes (41,5×24,8x14mm) (FREEEMG, BTS Bioengineering, Milan, Italy) will be used to record EMG. Twelve pairs of EMG electrodes will be positioned over 6 abdominal and 6 back muscles bilaterally on: Thoracic Erector Spinae (TES) Lumbar Erector Spinae (LES), latissimus dorsi (LD), Rectus Abdominus (RA), obliquus externus abdominis (EO) and obliquus internus abdominis (IO).

Prior to the application of electrodes, the skin in the region on abdomen as well as lateral to the lumbar and thoracic spine will be prepared by shaving the area if needed and then applying an abrasive paste (SPES Medica, Italy), and finally cleaning the region with water.

Experimental procedure

Experiment 1:

Following preparation, the subject will be asked to stand still with all markers as well as electrodes on, to capture a static trial. Then, the subject will be asked to sit on a stool with their arms crossed and folded on the chest (except for the side bending movements, when they'll be asked to extend their arms by their sides and touch a target on the right and left side when they move), and their feet rested on a wooden step to position hips and knees at 90º flexion. A laser pointer will be attached using a double sided tape on the participant's sternum (5 cm below the sternal notch). Participants will be asked to perform continuously 30 cycles of repeated trunk (flexion/extension, right/left rotation, and right/left lateral bending) at three speed levels. To standardize the trunk range of motion between participants, they'll be asked to touch 4 targets with the laser pointer. Upper and lower targets for the flexion (35º) and extension (15º) movements. Right and left targets for the rotation movements (30º). While for the side bending (15º), they'll be asked to maintain the laser pointer in the middle while touching with their hands a lower target right/left on each side. In order to set up these targets the trunk range of motion will be measured in degrees with a mobile phone application as an inclinometer at the level of the 12th thoracic vertebra (Pourahmadi et al., 2019a).

The speed of the movement for the slow and fast movement will be controlled using a metronome (mobile phone application) to establish the movement pace, which will be set at 30 (slow) and 50 (Fast) beats per minute. To ensure a smooth complete cycle of movement, the participant will be asked to touch a target with each beat (total of 60 beats for 30 cycle). To ensure 30 movement cycles per trial, the slow paced trials will be 120 seconds in duration, while the fast paced trials will be 72 seconds in duration. Although all movement cycles of each trial will be recorded, only the middle 15 cycles will be analysed to ensure steady-state movement behaviour (Granata and England, 2006a). They'll be asked to repeat every trial 3 times with 90 seconds of rest between each trial. A practice trial of 3 cycles will be allowed before the actual recording

Experiment 2:

The same participant preparation steps will be performed in this experiment. And the participant will be asked to perform 3 trials of the same tasks at three speeds with 90 seconds rest between each trial. But in order to induce fatigue, participants will be asked to maintain an Ito test for the back extensors only (Ito et al., 1996). Ito test is a safe and easy method to test both trunk flexor and extensor endurance with no need for special equipment. The participant will be asked to lie on their abdomen on a plinth with a digital goniometer on their side to measure the angle of the trunk while they bend backward. A twin-axis SG150B digital goniometer will be used by attaching one axis to the mid-axillary line and the other axis to the greater trochanter (Sanderson et al., 2019b). When the participant is positioned in prone position on the plinth, the resting angle will be calibrated as 0°. Subjects will be asked to raise their upper body by ~15°while holding the sternum off the plinth. A small pillow will be placed under the lower abdomen to decrease the lumbar lordosis. During this procedure, subjects will be asked to maintain their maximum flexion of cervical spine, with pelvic stabilization through gluteal muscle contraction. Participants will be permitted to complete a short 5-s contraction to ensure they have the correct technique **(Figure 2)**.



Figure 2: The position for testing the endurance of the back extensor muscles.

The subject will be asked to maintain the original position for as long as possible, not exceeding a 5 minutes time limit. The endurance time (seconds) for which subjects could maintain the position will be recorded using a stopwatch. The rate of perceived exertion (RPE) will be recorded as well at 15 seconds intervals and immediately following task failure using the Borg RPE scale.

After performing the lumber endurance task, participants will be again asked to perform the same continuously repetitive movement that were performed before the endurance task.

Summary of both of experiments design is shown in **Figure 3.**

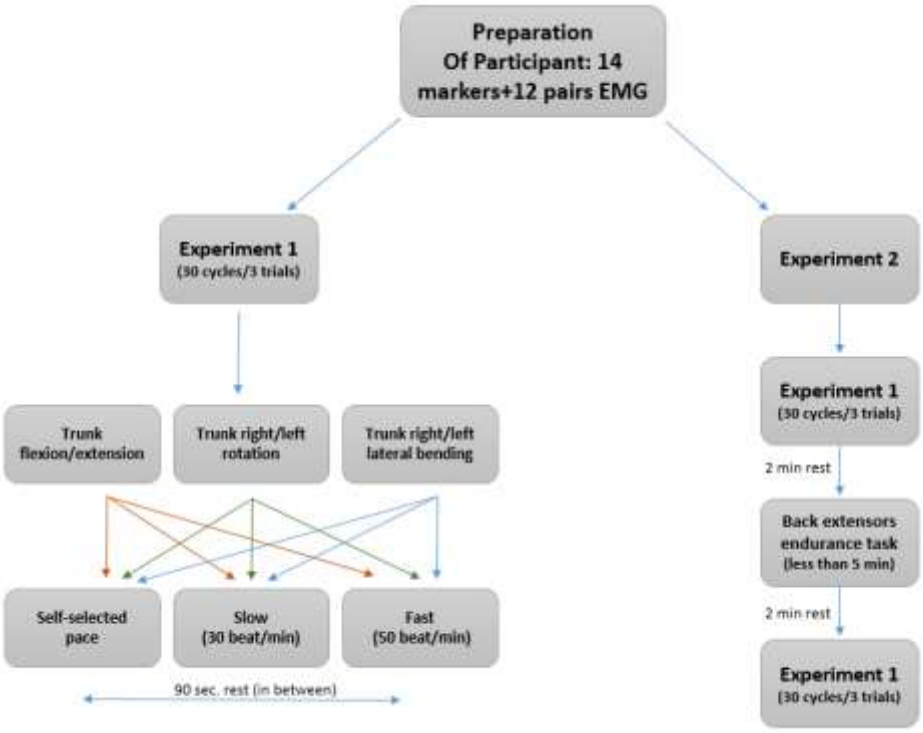


Figure 3: Summary of experiments 1 and 2 study design.

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.

Sample characteristics:
Total of 120 participants will be needed; 30 healthy and physically active participants & 30 participants who are experiencing CNSLBP will be recruited for each experiment.

Inclusion criteria:

- Both females and males are eligible for the study.
- The age range will be restricted to 18- 55 years to limit age effects on physical measures of the lumbar region.
- LBP and control participants must 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 CNSLBP will be considered for the study.

The following definition for CNSLBP 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
- 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).
- Participants currently under active treatment via the NHS will be excluded.

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 who meet the criteria, will be recruited from the University of Birmingham staff / student population and Birmingham's community. Recruitment methods will consist of information leaflets posted throughout the University of Birmingham's departments, via e-mails, via social media (the CPR spine Twitter account: @CprSpine will be used to advertise the posters) and word of mouth. Additionally, people on the CPR Spine register (a list of people with spinal pain) will be contacted.

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.

Once a potential participants contacts us about their interest in the study, we will email them a participant information sheet. This will include a detailed description of the experiment, including the purpose of the study and related requirements. When the attend the session and before obtaining participant consent, a verbal explanation of all procedures will be given by the researcher and they will have time to ask questions. Once they agree to participate in the study, they will then have to sign a written informed consent form. Please see attached the Participant Information Sheet and Consent forms.

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 receive a summary report of our research findings which will be sent to them via e-mail. They will not receive individual reports.

Additionally, the researchers will be happy to answer any questions regarding the purpose of the study and/or measurement procedures.

13. PARTICIPANT WITHDRAWAL

b) Describe how the participants will be informed of their right to withdraw from the project.

At any time up to two weeks post data collection, participants will have the right to withdraw from the project without any justification. This will be clearly reported on the Consent Form and Participant Information sheet and will be also expressed to the participants verbally.

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.

In case of participants' withdrawal, all data acquired up to that moment will be deleted and will not be used for analysis. Participants will be informed about this and their withdrawal will not result in any consequences.

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 have the choice to decide to be compensated with either research hours or the amount of £7.5 for each hour spent in the lab (£15 in total) The full experiment will last approximately two hours.

If participants choose to withdraw, how will you deal with compensation?

If participants withdraw prior to completion of the full study (i.e. 2 experiments), they will be compensated for the time spent in the lab.

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.

Participant anonymity will be maintained all times, by assigning each one of them to a randomised ID number.
This number will be used to collect and store all data accordingly. The necessary personal information that will
be collected on the consent form during this study (participant's name, gender, date of birth, telephone number
and email) will be securely stored and locked in a cabinet, in Professor Falla's office. Only the researchers (Amal
Alsubaie, Dr Eduardo Martinez-Valdes, and Professor Deborah Falla) will have access to it.

All the collected data from measurements will be saved on a secure (password protected) strictly confidential University of Birmingham server. Additionally, data collected via the tablet PC will be password protected with all subjects' files being stored with the assigned ID number. The data will only be shared with the participant, investigator and research team. They will not be disclosed by a third party.

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 electronic data will be securely stored (in an electronic format) on the secure University of Birmingham server.
Only the researchers (Amal Alsubaie, Dr Eduardo Martinez-Valdes, and Professor Deborah Falla) will be able to
access the data. Access to data will require a password and all data will be managed in accordance with the General Data Protection Regulation (GDPR).

After the completion of all measurements, all consent forms containing personal data will be securely stored in a locked filing cabinet in Professor Falla's Office with authorised access only to the investigators.

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 is the first to use the parameters of the helical axis (HA) to explain the motor variability of the trunk. We expect that this study will provide new insights about the quality of the multi-segmental motion of the human trunk. In addition, this will give us a better understanding of how people move in response to low back pain.

We believe that this study will provide important information about the impairments induced by low back pain and will help to provide future recommendations for the management of this condition.

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. All participants will be advised that they can stop the experiment at any time.

Non-invasive mounting/attaching procedures of surface electrodes include slight discomfort from minor abrasion of the skin area. Prior electrode placement, the skin will need to be shaved to remove any hair. However, single use disposable razors will be used thus there is no expected risk from this procedure.

Participants will be informed that they may experience some mild discomfort while performing the tasks. Because of their simplicity, the motor tasks accomplished by the participants will not lead to anxiety or stress higher than that already expected from everyday life. To deal with the above, appropriate rest time will be provided throughout the experimental trials. Additionally, extra rest periods will be given to the participants at any time, if they need it.

The similarity of going to the gym and performing unaccustomed exercise will be used to explain this sensation to the participants, where a discomfort or muscles soreness is usually felt the next day but is transient and resolves after a couple of days. Such response to isometric exercise is normal and it does not provoke any long-lasting effects.

Kindly also see attached the Risk Assessment Form.

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.

Not applicable

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:	13/03/20

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.

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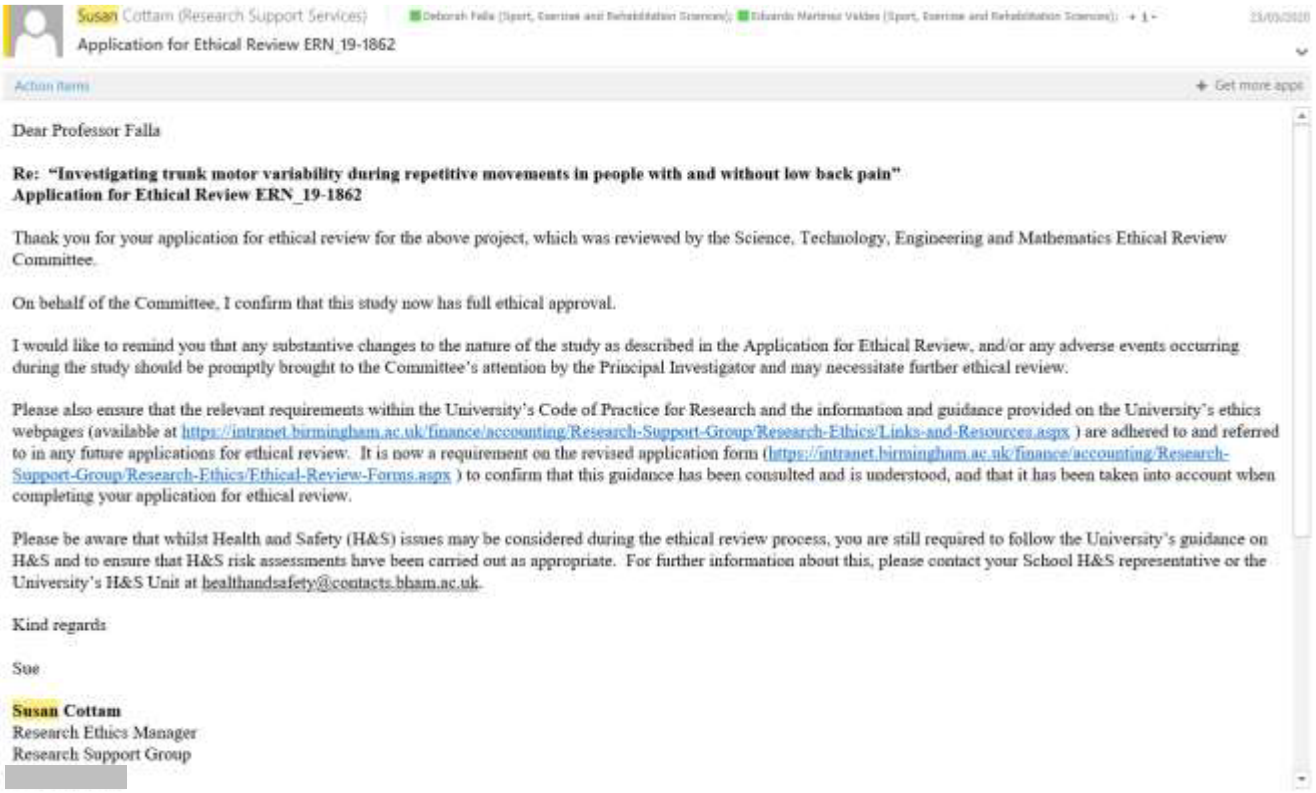
Amendments

We would like to thank the Ethics Committee for their time and constructive points. Answers to all your points can be found in the table below.

Points raised by ethics committee	Response
• The Committee requested copies of all questionnaires to be used in the study.	Please find attached all five questionnaires in the email attachments.
• Please provide further detail on the proposed use of social media to recruit – does CPR Spine have a dedicated social media presence (e.g. Facebook account) or will other sites be used?	**File:** 1_UoB Level Ethics Application form_AA We added the CPR spine Twitter account highlighted as follow: via social media (the CPR spine Twitter account: @CprSpine will be used to advertise the posters)
• Why will participants currently under treatment via the NHS be excluded from the study? Does this unnecessarily exclude individuals who could have made a useful and valid contribution to the study?	Participants currently under active treatment via the NHS will be excluded in order to exclude any factors that may interfere with the outcome measures (e.g. any active treatment that may reduce their chronic pain) as well as to make sure that the LBP is present at the time of testing.
• Please consider whether age may be a confounding variable – is it likely that older healthy adults are more likely to have restricted movement whilst not self-reporting as having lower back pain?	The age range will be restricted to 18- 55 years to limit age effects on physical measures of the lumbar region. Taking into consideration that the main aim of the study is to explore the movement variability (that may give an indication about the quality of movement) as a response to chronic pain regardless whether they may present with age-related movement restrictions or not. We will consider age in the statistical analysis of the data.
• Is there any risk that for lower back pain participants, the experiments (particularly experiment 2) could aggravate their condition? If so, what steps will be taken to mitigate this?	**File:** 5_Hazard and Risk Assessment Summary Form_ AA An appropriate rest time will be given as mentioned to the participant in between trials and when they ask for rest. The RPE scale will be used to monitor each person during the experiment. Participants will be advised that they can stop the experiment at any time. They will also be advised that they may feel soreness after the session similar to pain/muscle soreness that we felt after doing unaccustomed exercise at the gym. This usually does not last longer than 24-48h. They will be advised to contact an investigator if their pain persists.
• Further information was requested on the nature of all	**File:** 1_UoB Level Ethics Application form_AA

personal data to be collected, who will have access to it, and the arrangements for data retention and disposal.	We added the highlighted text: The necessary personal information that will be collected on the consent form during this study (participant's name, gender, date of birth, telephone number and email) will be securely stored and locked in a cabinet, in Professor Falla's office. Only the researchers (Amal Alsubaie, Dr Eduardo Martinez-Valdes, and Professor Deborah Falla) will have access to it.
• Please consider whether the provision of research contact hours is an appropriate form of compensation for all control participants (i.e. both students and staff). Might it be preferable to offer all groups payment (as is currently the case for the lower back pain group)?	We have modified the compensation following this suggestion as highlighted below: **File:** 1_UoB Level Ethics Application form_AA Control and LBP group participants will be will have the choice to decide to be compensated with either research hours or the amount of £7.5 for each hour spent in the lab. The full experiment will last approximately two hours. **File:** 2_1Recruitment poster - Healthy_ Speed&Fatigue_AA For completing this study, we are able to award - 2 Research hours if needed - or £15 **File:** 3_1Participants_Info_Sheet_Healthy_participants_Speed&Fatigue_AA The experimental session will last approximately two hours and you will have the choice to decide to be compensated with either research hours or the amount of £7.5 for each hour spent in the lab (£15 in total).
• Might lower back pain participants request individual feedback on what the experiment reveals about their own condition, and if so, how will this be handled?	**File:** 1_UoB Level Ethics Application form_AA The highlighted text was added to the participant feedback section: Participants will be invited to receive a summary report of our research findings which will be sent to them via e-mail. They will not receive individual reports. Additionally, the researchers will be happy to answer any questions regarding the purpose of the study and/or measurement procedures.

• It was noted that currently, there are 4 participant information sheets comprising 2 each of 2 different titles. Only 2 information sheets are required, and each should bear the same title, with one for the lower back pain group and one for the control group (the same applies for the adverts).	**Files:** 2_1Recruitment poster - Healthy_ Speed&Fatigue_AA 2_2Recruitment poster - LBP_ Speed&Fatigue_AA 3_1Participants_Info_Sheet_Healthy_participants_Speed&Fatigue_AA 3_2Participants_Info_Sheet_LBP_participants_Speed&Fatigue_AA Two information sheets with two adverts were created, for each group with the same title.
• It was felt that participants should be given the information sheet in advance of the experiment so that they have time to consider whether they wish to participate, rather than being given it at the beginning of the experiment. The verbal explanation of procedures and an opportunity to ask questions should take place at the beginning of the experiment.	**File:** 1_UoB Level Ethics Application form_AA Once the potential participant contact us about their interest in the study, we will email them with the participant information sheet. This will include a detailed description of the experiment, including the purpose of the study and related requirements. Before obtaining participant consent before the beginning of the experiment, a verbal explanation of all procedures will be given by the researcher and they will have time to ask questions. Once they agree to participate in the study, they will then have to sign a written informed consent form. Please see attached the Participant Information Sheet and Consent forms.
• Regarding the recruitment advertisements, can individuals respond to adverts for both experiments? It was suggested that it might be better to have one advertisement covering both control groups and one covering lower back pain participants, rather than separate adverts for each experiment. You could then randomly assign participants to experiment 1 or experiment 2.	**Files:** 3_1Participants_Info_Sheet_Healthy_participants_Speed&Fatigue_AA 3_2Participants_Info_Sheet_LBP_participants_Speed&Fatigue_AA The following highlighted text was added after combining the two information sheets: You will be asked to visit the Movement Analysis Laboratory (Room G64) in the School of Sport, Exercise and Rehabilitation Sciences. Then you will be randomly assigned to either experiment 1 or experiment 2.



Susan Cottam (Research Support Services) Deborah Falla (Sport, Exercise and Rehabilitation Sciences); Eduardo Martinez Valdes (Sport, Exercise and Rehabilitation Sciences); + 1 - 23/03/2020

Application for Ethical Review ERN_19-1862

Action Items + Get more apps

Dear Professor Falla

Re: "Investigating trunk motor variability during repetitive movements in people with and without low back pain"
Application for Ethical Review ERN_19-1862

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 brought 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

Sue

Susan Cottam
Research Ethics Manager
Research Support Group

Consent Form

Study Title	**Investigating trunk motor variability during repetitive movements in people with and without low back pain**		
Participant Name:		**Date:**	
Researcher Name:		**Ethics Number:**	

This information is being collected as part of a research project, which examine the variability of trunk movement in response to low back pain during a repetitive uniplanar movement. The research will be conducted at the School of Sport, Exercise and Rehabilitation Sciences at the University of Birmingham. The information that 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 2018. No identifiable personal data will be published.

This section to be completed by the participant:

Please tick the box at the end of each statement if you agree with it.

1. I confirm that I have read and understood the Participant Information Sheet for the above study. I have had the opportunity to ask questions and these have all been answered satisfactorily ☐
2. I. understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, up to two weeks after my last visit to the lab. ☐
3. I agree to the storage and use of my data for the purposes of this research study. ☐
4. Based on the above, I agree to take part in this research study. ☐

Signed:
Name in capitals:
Date:

This section to be completed by the researcher

I certify that this participant has read, properly completed and signed the screening and consent forms, witnessed by myself:

Signed:

Date:

By supplying this information you are consenting to the University storing your information for the purposes of the stated research study. The information will be processed by the University of Birmingham in accordance with the provisions of the Data Protection Act 2018. No identifiable personal data will be published

UNIVERSITY OF BIRMINGHAM | CENTRE OF PRECISION REHABILITATION FOR SPINAL PAIN

Investigating trunk motor variability during repetitive movements in people with and without low back pain

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.

What is the purpose of the study?

This study investigates the role of trunk movement variability in people with chronic low back pain (CLBP) compared to asymptomatic controls, during repetitive uniplanar movements (i.e. trunk forward /backward bending, right/left rotation, right/left lateral bending). Using the parameters of helical axis as a method to assess movement variability, we'll test the effects of changing speed of motion and fatigue. As well as observe the differences of muscle activity and recruitment patterns of the trunk muscles during these repetitive tasks. Changes in trunk motor variability will be assessed using 3D motion capture system synchronized with wireless non-invasive surface electromyography (EMG) to detect changes in muscles activity.

Why have I been chosen?

You have been chosen because we understand that you, as **healthy participant**, could represent a normal reference in this study. The inclusion criteria to take part in the study is being between 18 and 55 years old and the **absence** of history of concurrent systemic issues including rheumatic and neuromuscular disorders, history of chronic respiratory or neurological problems, spinal deformity or surgery, cardiovascular conditions, pregnancy and history over the last three years of back or lower limb pain or injury that limited your function and/or required treatment from a health profession.

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.

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.

The experimental session will last approximately two hours and you will have the choice to decide to be compensated with either research hours or the amount of £7.5 for each hour spent in the lab (£15 in total). If you decide to withdraw during the experimental session we will proportionally compensate for the amount of time that you spent performing the experiment.

What will happen if I decide to take part?

You will be asked to visit the Movement Analysis Laboratory (Room G64) in the School of Sport, Exercise and Rehabilitation Sciences. Then you will be randomly assigned to either **experiment 1** or **experiment 2.**

Experiment 1:

- Complete a questionnaire which asks you about your physical activity levels.
- You will be asked to sit on a stool with your arms crossed and folded on the chest (except for the side bending movements, when you'll be asked to freely hang your arms by your sides) and your feet will be rested on a wooden step.
- You will be asked to perform continuously 30 cycles of repeated trunk (forward/backward bend, right/left rotation, and right/left lateral bending) at three speed levels. With a laser pointer, attached on your sternum using a double sided tape, you'll be asked to reach 4 targets. Upper and lower targets for the forward/backward bend movements. Right and left targets for the rotation movements. While for the side bending, you'll be asked to maintain the laser pointer in the middle while touching with your hands a lower target right/left on each side.
- The speed of the movement will be controlled using a metronome (mobile phone application) to establish the movement pace. To ensure 30 movement cycles per trial, the slow paced (30 beats per minute) tasks will be 120 seconds in duration and the fast paced (50 beats per minute) tasks will be 72 seconds in duration. While the self-paced tasks will be 30 movement cycles per trial but the time and speed will not be controlled. You'll be asked to repeat every trial 3 times. However, resting periods will be frequently allowed to avoid any kind of discomfort or exhaustion.

Experiment 1:

You'll be asked to perform the same previous continuous repetitive cycles of trunk movements before and after an endurance task that involves the following:

- You'll be asked to lie on your stomach on a plinth with a digital goniometer on your side to measure the angle of your trunk backward bending.
- You'll be then asked to raise your upper body off the plinth.
- You'll be asked to maintain this position for as long as possible, not exceeding a 5 minute time limit. The endurance time (seconds) will be recorded using a stopwatch.
- Using a scale to rate the perceived exertion we will ask you at 15 seconds intervals and immediately following the endurance task.

While performing above-mentioned experiments, the three-dimensional movements of the trunk will be captured using eight infrared cameras in order to track 14 markers (14mm) attached on your skin on your back along the spine. Additionally, the electrical activity of your muscles will be recorded with a wireless surface electromyography (EMG) that will be placed over your back and abdominal region. We will ask you to bring shorts and a top that leaves your back and abdomen accessible for this session.

What are the potential benefits of taking part?

This study will provide important information about the impairments induced by low back pain in term of movement variability and may help to provide future recommendations for the management of this condition. You will also gain a better understanding of how your trunk move in response to pain and your muscles activate during repetitive movements which resemble activities of daily living (ADL) (e.g. trunk bending to load a dishwasher). You are welcome receive a summary report of our research findings at the end of the study however, we cannot provide individual reports.

What are the potential risks of taking part?

Non-invasive mounting/attaching procedures of surface electrodes include slight discomfort from minor abrasion of the skin area. Prior electrode placement, the skin will need to be shaved to remove any hair. However, single use disposable razors will be used thus there is no expected risk from this procedure. You may also experience some mild discomfort or muscles soreness especially following the **experiment 2** and this is usually felt the next day but is transient and resolves after a couple of days. It is a similar sensation after going to the gym and performing unaccustomed exercise. If you continue to experience discomfort after 72 hours then you should contact the investigator. You are also free to stop the experiment at any time.

Will my participation be 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. Data will be kept for 10 years in accordance with the EU General Data Protection Regulation 2018 and the University of Birmingham Research Guidelines. All data for presentation will be anonymised and aggregated,

so your identity will not be revealed in any way. You can withdraw your data until two weeks from data collection.

What will happen at the end of the research study?

The findings from this study will be presented 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 low back pain. All data for presentation will be anonymised, that means your identity will not be revealed in any way.

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 Amal Alsubaie and is overseen by Professor Deborah Falla, Chair in Rehabilitation Science and Physiotherapy .

What if I have a problem or concern?

If you have a concern about any aspect of this study, please speak with Professor Deborah Falla or Amal Alsubaie

For further information please contact Amal Alsubaie

Amal Alsubaie Centre of Precision Rehabilitation for Spinal Pain School of Sports, Exercise and Rehabilitation Sciences University of Birmingham B15 2TT	

Thank you for your interest in participating in our study!

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Why have I been chosen?

You have been chosen because we understand you are between 18 and 55 years old and you have had **Low Back Pain** which you do not know the cause of (i.e. with no diagnosis) for at least 3 of the last 6 months.

You cannot be selected for this study if you are not between 18-55 years old and you experience pain from your back radiating down to your leg. In addition, you cannot participate if you suffer from concurrent systemic issues such as rheumatic or neuro-musculoskeletal disorders. Moreover, you will be excluded if you have (current or past) neurologic problems (such as stroke. Furthermore, you cannot take part if you have been diagnosed with spinal fractures, disc herniation or spinal stenosis or if you are currently pregnant. Finally, you cannot participate if you are receiving LBP treatment at the time of the study (e.g. physiotherapy,) or taking certain medications (e.g. opioids, anticonvulsive, or regular high-dose anti-inflammatories).

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How does your spine move?



Purpose:

To examine the variability of trunk movement in response to changes in movement speed during repetitive trunk motion

We are currently recruiting people who:

- Are aged between 18-55
- Have **no history** of **low back pain**, chronic **neurological disorders** or other **musculoskeletal complaints** affecting trunk movements.

What do you need to do?

This study will involve 1 lab session (approximately 2 hours)

We will use a 3D motion capture system with surface wireless electromyography to measure the variability of your movement and muscle activity while preforming repetitive trunk movements in three different planes of motion.

For completing this study, we are able to award

- **£15**
- **or 2 Research hours if needed**

For more information or to take part, please contact Amal Alsubaie - [redacted]

[redacted]

UNIVERSITY OF BIRMINGHAM | CENTRE OF PRECISION REHABILITATION FOR SPINAL PAIN

Do you have Low Back Pain?



Purpose:

To examine the variability of trunk movement in response to changes in movement speed during repetitive trunk motion

We are currently recruiting people who:

- Are aged between 18-55
- Have had **Low Back Pain** for at least 3 months
- Your pain is not linked to trauma, fractures or spinal stenosis.

What do you need to do?

This study will involve 1 lab session (approximately 2 hours)

We will use a 3D motion capture system with surface wireless electromyography to measure the variability of your movement and muscle activity while preforming repetitive trunk movements in three different planes of motion.

For completing this study, we are able to award

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For more information or to take part, please contact Amal Alsubaie –