The Association Between Hip Hypomobility and Hypermobility, and Lumbar Symptoms in Adults Aged 40 Years and Older

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A Dissertation submitted to the Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Masters of Science in Physiotherapy.

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Declaration

I, Kevin Ermann, declare that this Dissertation is my own, unaided work. It is being submitted for the Masters of Science in Physiotherapy at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

Kevin Ermann

Name of candidate — Signature of candidate

6th day of April 2023 in Johannesburg

Dedication

To my parents, for their unwavering support

Abstract

Objectives: a) To better understand the association and potential causality of hip joint hyper/hypomobility on lower back pain. b) Determine whether an association exists between symptomatic lumbar ranges of movement (ROM) and their coupled hyper/hypomobile hip ROM. c) Compare hip rotation ROM across the 0º, 30º and 90º sagittal plane positions.

Design: A quantitative, cross-sectional, analytical study.

Participants: Two groups, with participants over the age of 40, were compared. Namely, 63 participants with chronic lower back pain (lumbar pain group) and 32 participants without (control group).

Outcomes measures: Data were collected on participant, activity and lower back pain parameters. Passive hip ROM was measured with an Inertial Measurement Unit (IMU). The differences between the lumbar pain and control group's hip ROM was analysed.

Results: a) No significant difference was found between the group's hip ROM, however 11 of the 15 tested side-to-side hip ROM variables showed significance in the lumbar pain group, while only five showed asymmetry in the control group. b) Only iliopsoas length showed some significance across asymptomatic, symptomatic and control lumbar extension pain subgroups. c) Left and right hip external rotation (ER) range varied significantly between each of the three sagittal positions. Although not always significantly different, right hip internal rotation (IR) followed a similar pattern between the three positions. Left hip IR ROM was less consistent across the three positions.

Conclusion: The treatment of hip ROM side asymmetries is a consideration in the management of non-specific lower back pain.

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

AAOS -	American Academy of Orthopaedic Surgeons
AIC -	Anterior Interior Chain
ASIS -	Anterior Superior Iliac Spines
CT -	Computerised Tomography
ER -	External Rotation
FAI -	Femoroacetabular Impingement
ICC -	Intraclass Correlation Coefficient
IR -	Internal Rotation
ITB -	Iliotibial Band
IMU -	Inertial Measurement Unit
MRI -	Magnetic Resonance Imaging
MTT-	Modified Thomas Test
OA -	Osteoarthritis
ROM -	Range of Movement
SLR -	Straight Leg Raise

Chapter 1 Introduction

1.1 Background

Historically, owing to the human body's complexities and having to master an enormity of information to understand its workings, medical practitioners and researchers have specialised in order to gain a deeper understanding of these biological systems and their pathologies. This for example, is evident in how manual therapy texts are compiled. The hip joint and lumbar spine are separated into different chapters and across different volumes (Hengeveld and Banks, 2014; Kaltenborn, 2011). There is a growing realisation that anatomical systems need to be studied more holistically to fully appreciate their functionality. This concept, termed "regional interdependence", encourages practitioners to look beyond the specific and discern whether neighbouring anatomical areas are contributing to a patient's symptoms (Wainner, Whitman, Cleland and Flynn, 2007; Sueki, Cleland and Wainner, 2013). Be this circumstance as it may, physiological movement through hip–lumbar spine coupling is long appreciated. Kapandji's text from as far back as 1974 brought this author's attention to the concept (Kapandji, 1974). Hip-spine syndrome, coined by Offierski and MacNab in 1983 (Devin et al., 2012), described the association and varieties of concurrent hip osteoarthropathy and lumbar spondylosis presentation. Still more recently, Lee (2011), using the term lumbopelvic-hip complex, acknowledged these structure's interaction in her book on the pelvic girdle.

As composite movement is determined by the sum of individual ranges from different joints along the kinetic chain, hypomobility or hypermobility of one of these components could change the axes of rotation of adjacent joints. This affects the chain's movement, potentially causing micro-instability and with it, symptoms (Sahrmann, Azevedo, and Van Dillen, 2017; Mitchell Jr and Galen Mitchell, 2002; Lee and Wong, 2002). For example, relative mobility's effects may be evident after spinal fusion, where the adjacent segments become degenerative, unstable or develop other pathologies due to mechanical stresses (Lee and Choi, 2015). Similarly and specific to this study, limited or excessive hip rotation ROM is believed to place excessive strain on the soft tissues and bone of the lumbar spine (Ellison et al., 1990). Sahrmann's (2002) textbook demonstrating clinical presentations, highlights these two adjacent regions' relative mobility and their interconnected role in symptom creation. These sentiments are affirmed in certain literature reviews (Zawadka et al., 2018) but questioned in others (Abady Avman et al., 2019). Recent research corroborating these views, demonstrated that a lower back pain group had less pelvic tilt ROM but greater lumbar motion when compared to the asymptomatic group (Reis and Macedo, 2015).

Likewise, hip movement dysfunction can also place strain on the lumbar disc. Combined lumbar movements place great stresses on the lumbar intervertebral discs (Neumann, 2017), resulting in annulus fibrosus micro-tears, disc herniation with substantial decrease in disc height and episodic lower back pain (Ogurkowska and Kawalek, 2016). Disc injury does not only occur with traumatic incidents, but small repeated "progressive" insults are also believed to be significant (Hadjipavlou et al., 2008). Inoue and Espinoza Orias (2011) noted that disc degeneration and particularly fissures in the annulus fibrosis, contribute to torsional instability. Further, a damaged disc loses its shock absorption capabilities, stimulating osteoblastic activity in the vertebral body (Ogurkowska and Kawalek, 2017). These pathological conditions may develop into a vicious cycle, whereby disc degeneration leads to instability, which in turn causes further degeneration.

As certain specific hip and lumbar ranges couple (Kapandji, 2011; Lee and Wong, 2002), it is of importance to know whether a particular hypomobile or hypermobile hip's range has a link to its coupled lumbar movement's symptoms. Additionally, as activities of daily living combine different hip ranges, having a greater appreciation of these ROM would also be of value. A vast amount of research has been devoted to determining what effect the 0º and 90º hip flexion position has on hip rotation range (Ellison et al., 1990; Simoneau et al., 1998; Young et al.,2014; Aefsky et al., 2016; Roach and Miles, 1991; Roach et al., 2013; Roach et al., 2015; Van Dillen et al., 2008; Ellenbecker et al., 2007; Kouyoumdjian et al., 2011). To the author's knowledge, hip rotation range in the 30º flexion position has not been considered. As it is common practice to move and perform in stooped positions (for example, during housework and when playing golf) this functional position also warrants investigation.

By virtue of the pain's location and its neural influence, lumbar conditions are often treated locally, at the source of the complaint (Maitland, 1986). This "top-down" assessment and treatment approach, namely for symptoms that arise from (Maitland, 1986) and because of a local spinal fault, has had its successes but does not offer every patient resolution of their problem. Since considerable activity takes place in weight-bearing positions and through this capacity acts as a potential propagator of lower back pain, the hip joint's effects on lumbar movement necessitates exploration (Sadler et al., 2017). Greater understanding of this biomechanical chain would help unlock new avenues in the treatment of lumbar spine disorders.

1.2 Problem Statement

The lumbar spine and hip joint's interconnectedness is long under-appreciated by clinicians. Currently, the two region's problems are assessed, considered and treated in isolation. Amongst others, this lends itself to treatment failure, prolonged infirmity, poor quality of life; medical boarding; unnecessary surgery; misplaced biopsychosocial treatment referral and greater medical expenditure. More accurately these areas ought to be viewed as the lumbopelvic-hip complex, a single entity whose elements function together. A broader assessment should therefore be performed, identifying all dysfunctional components. Analysing these findings would lead to additional insights, enhancing treatment outcomes.

This research will help elucidate the hip and spine's relationship. Investigating whether patients with lumbar symptoms present with hypomobile or hypermobile hips; looking at whether side-to-side hip range asymmetries occur in individuals with lumbar symptoms; considering the relationship of asymptomatic hypomobile or hypermobile hips with their coupled, symptomatic lumbar movements and determining whether different positions of hip flexion affects hip rotation ROM. Gaining greater clarity on the complex's functionality will enhance its treatment, empowering clinicians to better manage its symptoms.

1.3 Aims and Objectives

The primary aim of this study was to establish the association between hip and lumbar ROM in adults with and without low back pain.

In order to achieve the primary aim, the objectives of this study are:

1. Determine the passive hip ROM of adults with and without low back pain namely, hip flexion; hip extension in prone; Thomas test (to measure iliopsoas length); straight leg raise (SLR); abduction; adduction and hip internal and ER ROM in prone, sitting and supine on a 30^{o} framework.

2. Compare the hip ROM (obtained in objective 1) in adults with and without low back pain.

3. Compare the hip ranges' side-to-side differences (asymmetry) in adults with and without low back pain.

4. Determine the symptomatic active lumbar ROM in the adults with low back pain namely, lumbar flexion, extension, left and right lateral flexion, left and right rotation and squatting.

5. Establish whether there is an association between hypomobile and hypermobile hip ranges and these symptomatic lumbar ranges in adults with low back pain.

The secondary aim of this study is to determine whether differing positions of hip flexion impact on hip rotation ROM.

In order to achieve the secondary aim, the objectives of this study are:

6. Determine hip rotation ROM in three different hip flexion positions, namely with the hip in 0º, 30º and 90º of flexion.

7. Compare hip rotation ROM in three different hip flexion positions, namely 0º, 30º and 90º.

1.4 Significance

As a supplement to the objective of determining passive hip ROM, the study will add to the existing body of normal hip ROM values. It will help establish whether asymptomatic hypomobile or hypermobile hip ranges are associated with symptomatic lumbar disorders. It will confirm whether hip range side asymmetries are more prevalent in persons with lower back pain. Furthermore, it will determine if there is a link between specific abnormal, asymptomatic hip ROM with their coupled symptomatic lumbar ROM. It will also substantiate whether differing hip flexion positions impact on hip rotation ROM. Lastly, it will form the basis for future research investigating hip joint treatment as an adjunct to lower back pain management. This would facilitate the expeditious treatment of lumbar complaints, enabling a reduction in medical expenditure.

1.5 Outline of this Dissertation

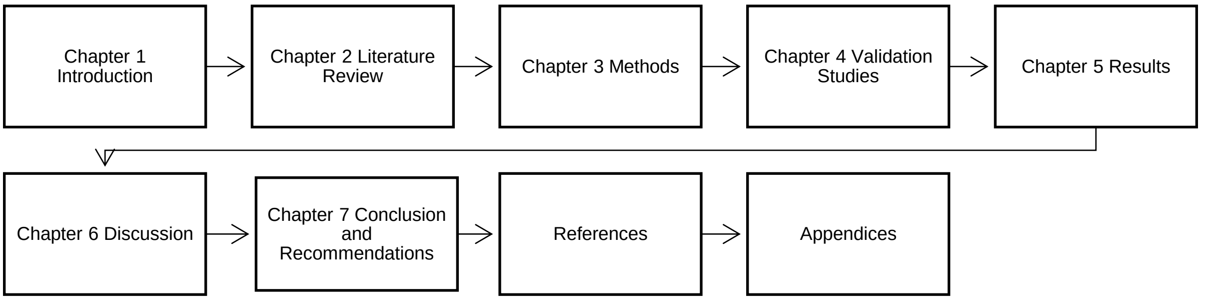

Fig. 1. 1 Outline of this dissertation

Chapter 2 Literature Review

2.1 Introduction

This literature review focused on the epidemiology of non-specific lower back pain, hip hypomobility, hip hypermobility and the association of hip hypo- and hypermobility with non-specific lower back pain. For contextual purposes, the hip's skeletal and ligamentous anatomy; the hip's ligamentous, labral and peri-articular muscle biomechanics; the lumbar spine's skeletal and intervertebral disc anatomy; the lumbar spine's arthrokinematics and the intervertebral disc's biomechanics and pathomechanics were also researched. Literature pertaining to the study's objectives was also reviewed. Namely, earlier research on hip normal values; the effects of age and gender on these normal values; the anatomical factors affecting each hip range's outcomes; the hip ranges' side-to-side asymmetries; the effects of hip flexion position on hip rotation ROM and each hip ranges' association with its coupled symptomatic lumbar range. Reviews were also performed of the Beighton Scale and the Baecke Questionnaire research - tools employed in the study.

2.2 Search Strategy

Medline via Pubmed and Google Scholar was searched using relevant phrases. Google Scholar's citation and related articles functionalities were also employed to identify more recent publications. Only English publications were included in this literature review. Articles published since the database's inception, up until November 2022 were considered for inclusion.

2.3 Epidemiology of Non-Specific Lower Back Pain and Hip Hypo- and Hypermobility

Lower back pain, a symptom rather than a diagnosis, is commonly seen in a form which can not be linked to a pathoanatomical source - this characteristic feature defines non-specific lower back pain (Maher et al., 2016). Due to this trait, the disorder is inherently difficult to treat. A reduction in symptoms being a more realistic treatment goal than full resolution of the problem (Maher et al., 2016). The epidemiology of the condition and that of hip hypo- and hypermobility are discussed below.

2.3.1 Epidemiology of Non-Specific Lower Back Pain

Lumbar pain is a universally debilitating condition and is now globally the leading cause of disability (Hartvigsen et al., 2018). In South Africa, low back pain is the sixth most common complaint in the primary health care setting (Mash et al., 2012). This rising societal burden is due to longer life expectancy and growing population size rather than increased incidence (Hartvigsen et al., 2018). During the course of their lives, 85 to 90% of adults will experience an episode of lower back pain, of which between 2 and 5% will endure at least one episode annually (Bono, 2004), and 5 to 10% will have a chronic, disabling condition (Johnson and Thomas, 2010). Despite its prevalence, it is often difficult to isolate a specific source for an individual's low back pain. Although Magnetic Resonance Imaging (MRI) and Computerised Tomography (CT) scans are frequently used to aid diagnosis, it is not uncommon to see similar radiological changes in asymptomatic people (Hartvigsen et al., 2018).

An American nationally representative health survey of 19,441 workers, found that individuals in the construction and mining industries had the highest risk of any form of lower back pain. Workers in the maintenance and building cleaning sectors had the highest incidence of "frequent and severe" episodes of lower back pain; while

Individuals in computational and mathematical occupations had the lowest lower back pain prevalence (Luckhaupt et al., 2019).

The highest incidence of low back pain occurs in those aged 40 to 80 years (Hoy et al., 2012), peaking between the ages of 41 and 50 and declining thereafter (French et al., 2015). Meucci, Fassa, and Faria (2015) performed a systematic review to determine the prevalence of chronic lower back pain (the definition of which varied) across the general population in differing age groups and genders. In studies where there was a 75% or greater response rate, 4.2% of people between the ages of 24 to 39, 19.6% of those between the ages of 20 and 59 and 25.4% of individuals older than and equal to the age of 60, experienced chronic lumbar symptoms.

In the general population, women showed a 50% higher prevalence of lumbar pain than men (Meucci et al., 2015). This may be due to lower muscle bulk and bone density, differing anatomical features, pregnancy and menstrual related back pain, earlier maturation during puberty and hormonal differences seen in women (Trompeter et al., 2017).

2.3.2 Epidemiology of Hip Hypomobility

Restricted hip joint ROM has been linked to abnormal joint morphology, femoroacetabular impingement (FAI), osteoarthritis (OA), labral tears and "sport related groin pain" (Reiman and Matheson, 2013). Differing to a pathology, FAI is described as a skeletal morphological variant (Brukner et al., 2012). Three variants occur, a cam lesion, where additional bone is found at the junction of the femur's head and neck; a pincer lesion, characterised by a spur extending from and deepening the acetabulum and a mixed variant, a combination of the two (Brukner et al., 2012). In contrast, hip OA is a degenerative disease defined by changes to the cartilage, subchondral and trabecular bone (Pedoia et al., 2018); active synovitis and systemic inflammation (Abramoff and Caldera, 2020) and thickening of the capsule (Nho et al., 2013). Individuals with "sport related groin pain" present with reduced hip ROM (Reiman and Matheson, 2013) and adductor muscle weakness (Mosler et al., 2015; Nevin and Delahunt, 2014). The region's interdependent and overlapping anatomy leads to multiple presenting pathologies (Drew, 2016). These conditions' prevalence is outlined in detail below.

Hip joint version relates to the skeletal orientation of the femoral neck and acetabulum in the transverse plane (Sahrmann, 2002). The varying combinations of femoral and acetabular version have a bearing on the hip's IR and ER and flexion ROM (Chadayammuri et al., 2016; VandenBerg et al., 2017; Sahrmann, 2002). Identified on CT scan or MRI, femoral version is calculated by measuring the angle between an axis passing through the femoral neck and a reference line, parallel to the line joining the posterior aspect of the femoral condyles (Saliba, 2023). Similarly, the degree of acetabular version is measured on CT scan. Its orientation is confirmed by measuring the angle between a line joining the anterior and posterior acetabular margins and the perpendicular to a reference line, connecting either the femoral head centres, the posterior acetabular walls or the posterior aspect of the ischia (Knipe, 2022). Opinion on what constitutes normal femoral version varies greatly, ranging from 10^{o} to 25^{o} (Lerch et al., 2018; Koerner et al., 2013; Singh, 2019). Chadayammuri et al. (2016) defined angles of 10^{o} to 20^{o} as normal femoral version; angles $>20^{o}$ constituted femoral anteversion and those $<10^{o}$, femoral retroversion. Furthermore, they recognised normal acetabular version as angles of 15^{o} to 20^{o}; angles $>20^{o}$ denoted acetabular anteversion and those $<15^{o}$, acetabular retroversion.

Defining approximately 10^{o} of femoral version as the norm, Koerner et al. (2013), researching an ethnically diverse, non-pathological sample through CT scan, found 37.1%, 30.4% and 48.2% of African-American, White and Hispanic men respectively presented with normal version, while 47.8%, 48.2% and 44.6% of the cohort displayed anteverted femurs. Retroverted femurs respectively appeared in 15.1%, 21.4% and 7.2% of the group. Noting a propensity toward femoral anteversion in women, they found 41.2%, 62.4%, and 42.8% of their respective female African-American, White and Hispanic participants had the condition. Normal femoral version appeared in

35.3%, 18.8% and 42.8% and femoral retroversion exhibited in 23.5%, 18.8% and 14.4% respectively in this group.

Studying acetabular version in a group of Swiss participants with symptomatic hip disease, Lerch et al. (2018) described normal acetabular version ranging from 10^o to 25^o, acetabular anteversion as >25^o and acetabular retroversion <10^o. Twelve percent of their 538 MRI and CT scanned acetabulae were retroverted, 70% had normal version and 18% were anteverted. A second paper looking at the prevalence of acetabular version, utilised the uninjured hips of a younger German cohort (age 16 to 40) to negate the impact of osteophyte formation (Klasan et al., 2019). Investigating with CT scan, they established women had a greater acetabular version than men and that 10.4% of the sample showed a side difference >4^o. Making use of cluster analysis to group their participants, they found an average version of 17.3^o ± 4.8^o, with 69.4% of participants concentrated around this mean. One individual (0.25%) presented with an acetabulum that was angled below the horizontal (-7.4^o), while 20.5% of the group displayed a version of 5.6^o to 13.2^o (a mean of 10.7^o) and 9.9% exhibited a version angle 23.0^o to 28.6^o (mean of 25.7^o).

Epidemiological studies have illustrated the surprisingly high incidence of asymptomatic and healthy people that exhibit bony abnormalities making them susceptible to FAI(FAI) (Audenaert et al., 2012; Sankar et al., 2013). Of the 50 asymptomatic participants aged between 15 and 40 years, none of the participant’s scanned hips showed degenerative changes, but 39% displayed at least one morphological FAI risk factor (Kang et al., 2010).

With increasing life expectancy, a growing elderly population and obesity crisis, the prevalence of hip OA is rising, with the demand for Total Hip Replacement Arthroplasties expected to increase by 174% in the United States by 2030 (Nho et al., 2013). Globally, women have a greater risk of developing hip OA, ranging from 7.6 to 9.3%, while between 4.4 and 8.7% of men acquire the condition (Plotnikoff et al., 2015). Locally, a meta-analysis of two population-based studies, revealed that 1.9% of South Africans above the age of 55 have the disorder (Usenbo et al., 2015).

There is also evidence of multiple presenting pathologies. Radiological and clinical examination of 292 athletes, between the ages of 16 and 50 with symptomatic mechanical hip pathology, found 62% had features of OA, 35% presented with hip dysplasia, 63% exhibited impingement and 5% normal x-ray results (Nogier et al., 2010). Twenty-two percent of their dysplasia cohort also demonstrated signs of impingement. In contrast, a literature review noted young adult and middle-aged people with cam deformities showed an association and higher risk of developing hip OA, but a vast majority of individuals did not have significant OA, even at 19 years follow up (Sankar et al., 2013). Further research was suggested to determine any association of pincer lesions with OA.

Labral tears and chondral injury are caused by high loading and rotational forces leading to degenerative changes in the femoral head and acetabulum (VandenBerg et al., 2017; Kang et al., 2010). Heerey et al. (2019) reported on the prevalence of these intra-articular hip pathologies in athletes with and without hip and groin pain through systematic review and meta-analysis. Thirty-three percent of asymptomatic and 20% of symptomatic athletes had labral tears, while 10% of asymptomatic and 7 to 40% of symptomatic athletes had cartilage defects.

Lastly, due to its multiple pathologies and confusing presentations (Drew, 2016; Kerbel et al., 2018), sport-related groin pain frustrates diagnostic classification (Waldén et al., 2015). Studies on the prevalence of sport-related groin pain were sport-specific and quoted in conjunction with hip injuries (Waldén et al., 2015). Between 7 and 13% of senior men and women footballers, presented with groin injuries (Waldén et al., 2015), while hip and groin injuries were responsible for 5.5% of injuries in professional baseball (Coleman et al., 2016) and similarly comprised 5 to 6% of injuries in athletes of all ages across all sports (Kerbel et al., 2018).

2.3.3 Epidemiology of Hip Hypermobility

Although joint hypermobility is said to be generalised across the body or isolated to one joint, ascribed to genetic laxity or achieved after years of training (Phan et al., 2020), this author was unable to locate specific epidemiological data on the prevalence of non-symptomatic, non-pathological hip hypermobility in adult members of the general population. There were however Australian studies, for example, considering the lower limb joint hypermobility in elite ballet dancers' legs (40% have a hypermobile left leg and 44% have a hypermobile right) (Phan et al., 2020), but this was not specific to this research's needs and can not be extrapolated to the wider population.

Generalised joint hypermobility's prevalence is widely disputed. This may be because of the important effect ethnicity, age and gender has on the diagnosis. An additional confounding factor is that different Beighton scores have been used to define the condition, namely 4/9, 5/9 and 6/9 (Russek and Errico, 2016). Hypermobility is believed to be more common in "non-Caucasian" and female populations (Singh et al., 2017; Klemp et al., 2002). In an American study comprising Caucasian, Asian, Hispanic, African-American and other ethnicities, respectively representing 81.3%, 9.7%, 4.9%, 4.1% and 6.4% of their sample, "healthy" university students, aged between 17 and 26 were assessed, with a Beighton score of ≥ 5 defining (Russek and Errico, 2016). Overall, generalised hypermobility was found in 26.2% of their 268 participant cohort, in 36.7% of the women and in 13.7% of the men. Comparatively, a higher participant mean age of 39.3 years may have countered a lower Beighton threshold ($\geq$4) in a New Zealand study's results (Klemp et al., 2002). Their age and gender adjusted research (n = 792), found 6.2% of Maoris and 4% of Caucasians were hypermobile. This may be because hypermobility has been shown to be inversely proportional to age, its prevalence reducing by 1% for each year lived (Santore et al., 2020). In contrast, 43 % of Nigerians and 29.8% of Iraqi students have been reported to have the condition (Klemp et al., 2002). Locally Indians, Blacks, followed by Caucasians respectively account for the diminishing prevalence of hypermobility in our population (Klemp et al., 2002). Taking a different view, Singh et al. (2017) proposed and defined its existence in 5% of the population after the American Academy of

Orthopaedic Surgeons (AAOS) recommended a limit of two standard deviations outside the mean of joint ROM.

There is a highly significant association of generalised soft-tissue flexibility with skeletal pathologies (Santore et al., 2020). Although in an (American) adult (average age 33.3 years), symptomatic hip sample and defining hypermobility with a Beighton score of ≥4, they found 14.5% of their non-dysplastic cohort; 77.9% of those with hip dysplasia and without OA; 35.7% of participants with dysplasia and OA; 30.4% of FAI participants; 17.3% of OA sufferers; 46.9% of individuals with "other" diagnoses and 22.6% of their whole population (n = 1004) was hypermobile. Here, 57% of the women and 24.1% of men were reported hypermobile. In a similar Danish study, reporting on the prevalence of generalised joint hypermobility in patients (n = 145) with greater trochanteric pain syndrome, 11% of men and 25% of women in this cohort presented with a Beighton score of ≥5 (Reimer et al., 2019). The average age of their male and female participants was 63 and 53 respectively.

The effects of age and gender on hypermobility is discussed further in the Beighton scale section below.

2.3.4 Epidemiology of the Association of Hip Hypo- and Hypermobility and Non-Specific Low Back Pain

Recent research, although recognising the dual presentation of hip and lumbar disorders, conceded that the prevalence of hip-spine syndrome was unknown (Redmond et al., 2014). This may be because of the poor quality of evidence showing an association of hip ROM limitation with non-specific low back pain (Abady Avman et al., 2019). Contrary to the focus of this study, there is information on the incidence of symptomatic, OA hip joints with low back pain but it wide-ranging. French et al's. (2015) literature review reported a 21.2 to 61.5% prevalence, while their own research found a 66.7% prevalence for the two conditions presenting together. These conclusions were marred by a small sample size of only 24 participants.

2.4 Hip Anatomy and Biomechanics

2.4.1 Hip Skeletal Anatomy

The hip is an enarthrosis, a ball-and-socket joint comprising spheroidal surfaces (Kapandji, 2011). The joint surfaces are not perfectly spherical nor congruent. Loads cause flattening and widening and translation of the joint centre (Kalisvaart and Safran, 2015). The acetabulum facing anteriorly, inferiorly and laterally, incongruently receives the femoral head, running in a superior, medial and interestingly, anterior, direction (Kapandji, 2011). This skeletal orientation produces greater posterior bony strength and stability, allowing greater flexion and abduction than extension and adduction range, but necessitates soft tissue structures provide significant anterior support for the joint (Kalisvaart and Safran, 2015). These ligaments, by restricting hip extension, provide passive restraint, reducing the muscular action required in the standing position (Hewitt et al., 2002).

Hip ROM is affected by osseous and soft tissue checks depending on the direction of movement and applied force. The bone resists anterior, posterior and superior forces, while the soft tissues withstand medial, lateral and inferior ones (Smith et al., 2014). Medial shear forces are prevented by both soft tissue and skeletal constraints because of the acetabular and femoral neck’s oblique orientation in the transverse plane (Smith et al., 2014). Osseous impingement may play a role in pure adduction, Turley et al. (2013) making use of CT dynamic simulation, predicted contact between the lesser trochanter and the pelvis. A deficiency of bone in the anterior, posterior and superior portions of the acetabulum, for example in hip dysplasia and after acetabular osteotomy, sees increased forces on the soft tissue with resulting labral and hip capsule injury (Smith et al., 2014).

2.4.2 Hip Ligamentous Anatomy

The hip capsule comprises superficial longitudinal ligaments and a deep layer of circular fibres lined by a synovium (Hewitt et al., 2002). The deep layer, a "cylindrical sleeve", consists of longitudinal, oblique, arcuate and controversially, circular fibres running from the acetabular margin to the base of the femoral neck (Kapandji, 2011).

This capsule is strengthened anteriorly by two ligaments, the iliofemoral and pubofemoral ligaments (Kapandji, 2011). The iliofemoral ligament consists of a superior (lateral) and inferior (medial) band, both originating distal to the anterior inferior iliac spine. The inferior band traverses almost vertically, attaching distally along the medial portion of the intertrochanteric line. The superior band passes horizontally, inserting into the proximal, lateral part of the intertrochanteric line (Kapandji, 2011; Martin et al., 2008). It is further reinforced with deep recurrent fibres from the rectus femoris, a fibrous band emanating from the acetabular margin and an aponeurosis from gluteus minimus (Kapandji, 2011).

The pubofemoral ligament resembles a sling, wrapping inferiorly around the femoral neck (Martin et al., 2008). Attaching medially to the anterior surfaces of the iliopubic eminence and pubic arch, it runs laterally to imbed into the anterior aspect of the fossa, located anterior to the femur's lesser trochanter (Kapandji, 2011). Posteriorly, it inserts into the distal part of the intertrochanteric crest, inferior to the ischiofemoral ligament (Martin et al., 2008).

The ischiofemoral ligament, comprising two bands, reinforces the capsule posteriorly. Originating on the ischial part of the acetabular margin, the superior band runs superolaterally, merging with the zona orbicularis and attaches to the medial surface of the anterosuperior base of the greater trochanter (Martin et al., 2008; Kapandji, 2011). The inferior band lies more posteriorly inserting into the intertrochanteric crest (Martin et al., 2008).

Although historically depicted as a ligament passing circumferentially round the femoral neck, the zona orbicularis, consists of arcuate fibres passing on its superior, posterior and inferior sides (Wagner et al., 2012; Fuss and Bacher, 1991). It attaches anteriorly to the iliofemoral ligament (Fuss and Bacher, 1991). Superiorly its fibres are interwoven with those of the superior band of the ischiofemoral ligament and posteroinferiorly it blends with those of the inferior band of the ischiofemoral ligament (Wagner et al., 2012). It is therefore likened to a sling enveloping the posterior circumference of the neck of the femur (Wagner et al., 2012; Fuss and Bacher, 1991).

The hip capsule’s mechanical properties are not uniform. Hewitt et al. (2002) testing fresh frozen cadaver bone-ligament-bone specimens, found that the iliofemoral ligament can sustain greater tensile force and was significantly stiffer than the ischiofemoral ligament. Similarly, Wagner et al. (2012) found that hip ligament thickness varied. Testing mid-portion thickness of 10 cadavers’ ligaments using MRI, they found a mean of 6.9 mm for the inferior band of the iliofemoral ligament, 4.2 mm for the superior band of the iliofemoral ligament, 3.0 mm for the pubofemoral ligament, 2.0 mm for the ischiofemoral ligament and 4.1 mm for the zona orbicularis. The above factors may account for the higher clinical incidence of posterior hip dislocation.

The ligament of the head of the femur, formerly ligamentum teres, consists of three bundles originating from the acetabular notch and transverse acetabular ligament and inserting into the fovea femoris capitis (Kapandji, 2011). Although there was consensus that it plays a minimal mechanical role because excessive tension interrupts its blood supply to the femoral head (Fuss and Bacher, 1991; Kapandji, 2011), the greater debate surrounding its functionality is reviewed in section 2.4.3.6 below.

2.4.3 Hip Ligamentous Biomechanics

Each hip ligament's functionality is discussed in the ensuing paragraphs. This was prepared to give the reader insight into the anatomical structures that control hip range. A number of researcher's works have been drawn upon, each using a different methodology to derive their conclusions. Fuss and Bacher (1991) dissected and conducted a detailed morphological analysis of the hip's ligamentous system. Since they did not observe a uniform, distinct fibre system and found that each subdivision of the capsule had differing functionalities, they proposed additional ligament complexes. Their new classifications have not been adopted though. Testing the functionality of the hip's ligaments with graph-foil and measuring strips spanning two brass nails anchored to the acetabulum and femur, they considered a total of 60 positions, assessing combinations of five flexion-extension, four abduction-adduction and three rotation positions. In so doing, they were able to determine where ligaments had a restrictive and controlling effect. Martin et al. (2008) researched hip ligament functionality in dissected, mounted fresh-frozen cadavers. Internal and external hip rotation was measured, by goniometer in the sagittal plane, at 10^{o} extension, neutral and at 15 and 30^{o} of hip flexion. These ranges were compared after each ligament was resected thereby determining its joint stabilising function. Hidaka et al. (2014) measured hip ligament strain in fresh-frozen cadavers using a displacement sensor in a variety of joint positions. Lastly, Van Arkel et al. (2015) studied in vitro hip specimens mounted in a testing rig. They transected each ligament and measured the reduction in torque to determine its contribution to rotational restraint in 18 different positions.

2.4.3.1 The Iliofemoral Ligament's Biomechanics

The iliofemoral ligament, consisting of two bands, is generally considered to limit extension and plays a role constraining rotation. Hidaka et al. (2014) were of the opinion that the inferior band of the iliofemoral ligament was strained by maximum extension and when 10^{o} and 20^{o} of ER was combined with maximal extension. With some similarity, Fuss and Bacher (1991) found the inferior iliofemoral ligament principally restricts extension in extreme abduction, mid-range abduction and neutral. It also had a controlling effect on both internal and ER in all these positions. As with the other authors above, Van Arkel et al. (2015) found the inferior band played a major role limiting external and IR in neutral and extension. In contrast, Martin et al. (2008) believed the inferior band of the iliofemoral ligament (and the pubofemoral ligament) had no significant role in controlling internal ROM. They showed that the iliofemoral ligament performs an important function in restricting ER

The superior band of the iliofemoral ligament was significantly stretched by maximal ER (Hidaka et al., 2014). Although not specifically stated, it was also found to check ER in flexion and abduction (Van Arkel et al., 2015). Similarly, Fuss and Bacher (1991) found the superior (lateral) iliofemoral ligament restricted ER in increasing flexion and when combined with full abduction to slight adduction. Their "lateral part of greater iliofemoral ligament" prevented ER in extension to slight flexion when combined with end-range adduction to mid-range abduction. Martin et al. (2008) further observed that the superior band of the iliofemoral ligament limited IR, this contribution increased as the limb moved into extension.

2.4.3.2 The Pubofemoral Ligament's Biomechanics

The pubofemoral ligament is commonly thought to control extreme abduction, with the additional function of curbing rotation. Hidaka et al. (2014) concluded it was significantly strained in abduction and when in combined abduction and 10^o, 20^o and 30^o ER. Similarly, Van Arkel et al. (2015) found the pubofemoral ligament only significantly limited rotation when the joint was in full abduction but that it also played a role arresting external and IR when the hip was in extension and flexion, respectively. Fuss and Bacher (1991) determined it limited abduction from end-range flexion to extension, regardless of the rotation angle. Kapandji (2011) thought that it was the principal abduction restraint with a minimal contribution from the inferior band of the iliofemoral ligament. As mentioned above, Martin et al. (2008) was of the view that the pubofemoral ligament had no significant role in controlling internal ROM, but that the ligament was the main restrictor of ER in extension, supported by the inferior band of the iliofemoral ligament.

2.4.3.3 The Ischiofemoral Ligament's Biomechanics

There was widespread agreement of the ischiofemoral ligament's role in restricting IR. Martin et al. (2008) found the ischiofemoral ligament played the most significant role limiting IR in each of their four sagittal plane positions. This was echoed by Van Arkel et al. (2015), who believed that the ischiofemoral ligament was the primary IR restraint. Furthermore, they were of the opinion that it was of particular importance limiting combined flexion (≥ 30º), adduction and IR, as well as, flexion (≤ 30º), abduction and IR. Also appreciating the ischiofemoral ligament's effects in combined positions, Hidaka et al. (2014) found it was significantly stretched by 10º and 20º of abduction when combined with maximal IR.

As before, Fuss and Bacher (1991) further partitioned this ligament. Their superior ischiofemoral ligament prevented IR through the range, except when the hip was in end-range extension-adduction and flexion-adduction. It also checked adduction through flexion, unfettered by the amount and position of rotation. They also subdivided the inferior ischiofemoral ligament into a medial and lateral portion. The lateral part limited end-range flexion and flexion-adduction, regardless of its rotational position. The medial portion restricted flexion when in differing positions of abduction but was also unaffected by rotation.

2.4.3.4 The Zona Orbicularis' Biomechanics

Torsion and tightening of the zona orbicularis around the femoral neck is caused by sagittal plane movements (Fuss and Bacher, 1991). Functioning like a "locking ring", it also prevents distraction of the hip joint (Wagner et al., 2012).

2.4.3.5 The Superior Portion of the Capsule's Biomechanics

There is general consensus that the superior capsule limits hip adduction, although the specific ligament garners controversy. Kapandji (2011) opined that the superior band of the iliofemoral and ischiofemoral ligaments are principally responsible. Fuss and Bacher (1991) found their "superior posterior coxal" ligament, located on the superior side of the capsule, restricted end-range adduction in extension and neutral. Further, the superior ischiofemoral ligament prevented adduction in 40º and 80º flexion. The degree of hip rotation had no effect on either structure. Their "inferior posterior coxal ligament", situated posterosuperiorly, limited adduction in neutral and 40º hip flexion but only when coupled with end-range IR. Hidaka et al. (2014) found that adduction and combined 10º adduction and ER placed an insignificant strain on the superior iliofemoral ligament. As their focus was on the efficacy of certain clinical hip stretching positions, they regrettably did not consider the effect of adduction on the ischiofemoral ligament.

2.4.3.6 The Ligament of the Head of the Femur's Biomechanics

Opinion varies around the functionality of the ligament of the head of the femur. Some authors claim the ligament is taut when the hip is placed in combined flexion, adduction and ER (Kalisvaart and Safran, 2015; Van Arkel et al., 2015). Kapandji (2011) was of the opinion that it is only strained in adduction. Fuss and Bacher (1991), although finding it stretched in end-range adduction, with the anterior element also lengthening during IR and the posterior part stretching with ER, still concluded that the hip capsule is exclusively responsible for limiting adduction. Van Arkel, et al. (2015) thought it played only a minor role in controlling ER, significantly less than that of the superior band of the iliofemoral ligament.

2.4.3.7 Combined Movement's Effects on the Ligamentous System

Different test positions place a maximum strain on each specific ligament (Hidaka et al. 2014), with minimal shared interaction (Smith et al. 2014). There is evidence however, that in certain extreme positions, all the ligaments work in unison restricting the range. Kapandji (2011) was of the belief that all the ligaments become taut in extension. Similarly, Kalisvaart and Safran (2015) described a spiral "screw home mechanism", which tightens the three hip ligaments and zona orbicularis, compressing the femoral head into the acetabulum as the hip extends. The hip's closed-pack positions are implied in Fuss and Bacher's (1991) study but were not identified as such, possibly because these have no relevance to anatomists. This author's analysis of their results shows they identified two loci where each of the three main ligaments was the primary restraint for a component of that position. The first locus, was combined end-range extension, abduction and IR, where the medial iliofemoral, pubofemoral, and superior ischiofemoral ligaments was the primary restraint for each of these respective ranges. This corresponds with Kaltenborn's (2011) copy on the hip's close-pack position namely, maximal extension, medial rotation and abduction. Their second locus was end-range combined flexion, abduction and ER respectively tightened the "medial inferior ischiofemoral ligament", pubofemoral and superior (lateral) iliofemoral ligaments. Although not recognised by Kaltenborn, this may represent a second closed-pack position. These two closed-pack positions may be clinically useful in hip diagnostics and lumbar and hip treatment.

2.4.3.8 The Anatomical Restraints of Rotational Range in the Sagittal Plane

As the role of hip flexion angle on rotation range was an objective of this paper, it was thought prudent to discuss the anatomical factors that affects this outcome. Opinion varies with regards to the structures which restrict hip flexion. Historically, soft-tissue approximation, skeletal impingement, muscle tonus and the hamstring muscle have been offered as possible mechanisms (Fuss and Bacher, 1991). Certain authors (Kapandji, 2011; Kalisvaart and Safran, 2015) were of the belief that hip flexion caused relaxation of all the ligaments, creating osseous impingement of the anterosuperior aspect of the femoral neck and acetabular margin at the end of range (Kapandji, 2011). This increasing ligament laxity was believed to account for hip instability in this position, resulting in posterior hip dislocation (Kapandji, 2011; Martin et al., 2008). This notion was echoed by Turley et al., (2013), using CT dynamic simulation to determine end-range restraining anatomy, concluded that osseous impingement checked hip flexion. Likewise, Martin et al. (2008) noted increasing internal and ER range from 10º extension till 30º flexion leading them to conclude that "the hip rests in a looser state when in flexion". They however did not conduct any testing further into hip flexion range. In contrast, Fuss and Bacher (1991) found that their "lateral" and "medial" inferior ischiofemoral ligaments were the primary restraints of end-range flexion. Similarly, Van Arkel et al. (2015) observed the ischiofemoral ligament "cradles" the femoral head at end range hip flexion preventing posterior subluxation. They calculated that the capsular ligaments, ligamentum teres and the labrum were respectively responsible for 90, 1 and 9% restraint in combined flexion and IR. In the same way, in combined flexion and ER, the capsular ligaments, ligamentum teres and the labrum were respectively responsible for 86, 12 and 2% restraint.

2.4.4 Labral Biomechanics

Physiological translation between the articular surfaces is limited to 2mm or less by the hip's skeletal structure and tight-fitting labrum (Neumann, 2017). Although the anterior labrum has significant control over both internal and ER (Martin et al., 2008), the hip's ligaments provide the primary rotatory restraint throughout the joint's ROM followed by the labrum and ligamentum teres. The capsule therefore prevents labral impingement (Van Arkel et al., 2015).

The labrum does provide key mechanical stability though. Intra-capsular negative pressure has an effect on joint congruency, resisting dislocation and subluxation forces (Smith et al., 2014; Kapandji, 2011). Labral tears affects this joint seal, reducing the vacuum effect with a resulting increase in femoral translations (Martin et al., 2008). A hip joint with a labral tear requires 60% less force to distract (Kalisvaart and Safran, 2015).

2.4.5 Peri-Articular Muscle Biomechanics

Peri-articular muscle action is believed to further stabilise the femoral head in the acetabulum, with the iliopsoas resisting anterior translation forces (Kalisvaart and Safran, 2015). The capsule receives further reinforcement from the gluteus minimus, the reflected head of rectus femoris and iliocapsularis (Neumann, 2017). The musculature is also of importance in limiting adduction. Exploring the validity of the Ober test in testing iliotibial band (ITB) length, Willett et al. (2016) measured the adduction range with successive transections of this muscle, the gluteus medius, the gluteus minimus and hip capsule. They found statistically significant increases in range when the gluteus medius/minimus tendon and superior capsule was cut, the ITB surprisingly, played no role.

A reciprocal relationship exists between the ligaments and muscle bulk, anteriorly fewer muscles complement strong ligaments, while posteriorly a larger muscule bulk accompanies a weaker capsule (Kapandji, 2011).

2.5 Lumbar Anatomy and Biomechanics

2.5.1 Lumbar Spine Skeletal Anatomy

Each functional spinal unit is a three-joint complex (Cunningham et al., 2020), consisting of a superior (upper) and inferior (lower) vertebrae separated anteriorly by an intervertebral disc and posteriorly by the articular processes of the two facet joints (Dennison et al., 2008). Lumbar intervertebral movement is governed by the facet joints, which control the direction and amplitude of movement (Moramarco et al., 2020) and the intervertebral disc, which acts like a swivel (Kapandji, 2009).

Orientated toward the sagittal plane (Neumann, 2017), the superior articular process faces posteriorly and medially, while the inferior articular process faces anteriorly and laterally (Kapandji, 2009). This generally enables a predominance of movement in the sagittal plane, to a lesser extent range in the frontal plane and least in the transverse plane (Cunningham et al., 2020). The facet joint angle, that is, its angle in the transverse plane relative to the midline, increases from L2/3 to L5/S1. In asymptomatic men, it was 25.88^{o} at L2/3 increasing to 50.22^{o} at L5/S1; in asymptomatic woman the angles were 30.19^{o} at L2/3 and 52.06^{o} at L5/S1 (Liu et al., 2018). This angulation explains the contrasting intersegmental rotation range we see, outlined in the paragraph below.

Facet joint tropism is an asymmetry of the angle of a segment's facet joints, a difference of greater than 7^{o} has been determined to be definitive (Widmer et al., 2019). Gibbons and Tehan (1998) state that facet joint tropism is present in as much as 20% of all lumbar levels, rising to 30% at L5/S1. Furthermore, they maintain that 90% of lumbar pain and sciatica patients display tropism, with pain presenting on the side of the obliquely angled facet. There is no consensus as to whether facet joint tropism is due to congenital anomalies or degeneration; however, it has been found to be age-independent, suggesting it is an inherited attribute (Widmer et al., 2019). Individuals with disc disease have a higher occurrence of facet joint tropism which increases rotation when loads are applied, torsioning the segment and placing greater stresses on the annulus fibrosis (Cunningham et al., 2020). Although clear conclusions may be difficult to draw on intersegmental motion coupling, tropism was believed to affect spinal mechanics (Gibbons and Tehan, 1998). More recent research however suggests that facet orientation, relative to the sagittal plane, has a greater influence on movement than facet asymmetry (Widmer et al., 2019).

The sacral promontory, and by virtue the lower lumbar segments, is angled anteriorly and inferiorly averaging between 30º (Kapandji, 2009) and 40º (Neumann, 2017) to the horizontal. This inclination, vertical gravitational loading and anterior translation, inherently creates an anterior shear force in the lower lumbar spine, shifting the centre of gravity forward and generating the lumbar lordotic posture (Cunningham et al., 2020). This force is increased with an exaggerated lordosis, placing an immense load on the apophyseal joints.

2.5.2 Lumbar Spine Arthrokinematics

There is little debate concerning intervertebral flexion and extension arthrokinematics (Kapandji, 2009; Neumann, 2017). Flexion is widely accepted to comprise anterior rotation and translation, with extension incorporating posterior rotation and translation (Gibbons and Tehan, 1998). Different postural positions through the sagittal range do not create significant additional lateral bending or rotatory intersegmental movement (Berry et al., 2019).

Lumbar lateral flexion and rotation arthrokinematics however, have garnered great debate. These two movements do not occur in isolation but are believed to rather "couple" together, that is, segmental rotation realises some lateral bending and lateral bending sees some rotation. First proposed by Lovett in the early part of the 20th century (Mitchell Jr and Galen Mitchell, 2002) from cadaveric dissections, coupled motion was then further developed by Fryette mid-century and adopted by Kapandji in the latter part of the century (Legaspi and Edmond, 2007). Although evident and supported by many authors (Legaspi and Edmond, 2007), there is widespread controversy regarding this behaviour (Moramarco et al., 2020). The argument relates to whether these two motions occur in the same direction, for example on laterally flexing to the right, segments rotate in concert to the right, or in the opposite direction, namely on laterally flexing to the right, lumbar segments rotate to the left. Definitive conclusions are difficult to draw because intersegmental rotation amounts to a few degrees. Inconsistencies have been attributed to research methodology, age, gender, posture (Moramarco et al., 2020), facet joint tropism, intervertebral disc height (Gibbons and Tehan, 1998), sagittal plane positioning, the spinal level being tested, in vivo or in vitro testing and participant pathology and symptomology (Legaspi and Edmond, 2007; Cunningham et al., 2020). Cadaveric studies may offer precise measurements but are limited by the lack of muscle action and gravitational axial loading (Gibbons and Tehan, 1998). Studies have also suggested that coupling motion may vary depending on whether lateral flexion or rotation is the primary movement but this has not been verified (Legaspi and Edmond, 2007). Literature reviews on the subject in 1998 (Gibbons and Tehan) and 2007 (Legaspi and Edmond) did not find conclusive evidence of a consistent pattern of lumbar intersegmental coupling.

In recent years, in vivo studies offering precise measurements with CT scanning (Ochia et al., 2006) and 3D MRI (Fujii et al., 2007), found contralateral lateral flexion on rotation at L1/2 to L4/5 and ipsilateral lateral flexion on rotation at L5/S1, but were conducted in supine, without a gravitational compressive force. Newer technological advances may finally be offering some clarity. Shin et al. (2013) made use of upright MRI and dual fluroscopic imaging to measure eight participant's (aged 40 to 60), in vivo, loaded, segmental coupled motion during maximal active left to right lumbar rotation in standing. This apparatus has the ability to measure translations of less than 0.3 mm and angles of less than 0.7^{o}. They found all the segments rotated similarly in the direction of the physiological movement, but L2/3 and L3/4 (L2 to L4) laterally flexed in the opposite direction, and L4/5 and L5/S1 (L4 to S1) laterally flexed in the same direction. Namely, when the spine rotated to the right, L2/3 and L3/4 were side bending left and L4/5 and L5/S1 were side bending right. These opposing segmental side-bending motions compensate for eachother, maintaining the spine in relative neutral in the coronal plane. They did not observe any sagittal plane motion during these movements.

Corroborating these findings to some extent, Berry et al. (2019) also utilised upright MRI to assess every lumbar end range movement in participants without a history of low back pain. They similarly found that when the spine rotated, it displayed contralateral lateral flexion, for example, left rotation, produced segmental right lateral flexion; however, they did not report whether there were any differences between the upper and lower lumbar spine. Regrettably, they could not offer a definitive answer on coupling patterning during lateral flexion. Future technological advances may finally resolve these questions.

The forementioned skeletal morphology and lumbar arthrokinematics produce the following motion segment ranges. Combined intersegmental flexion and extension range of approximately 10^o at L1/2 to a maximum of 15^o at L5/S1; a unilateral intersegmental lateral flexion range of approximately 5^o from L1/2 to L4/5 and 4^o at L5/S1; and approximately 1 to 2^o of unilateral intersegmental rotation at different levels from L1/2 to L5/S1 (Neumann, 2017). Cunningham et al. (2020) note that the greatest amount of intersegmental flexion range occurs at L3/4 and L4/5, 12^o and 13^o respectively, while L5/S1 averages 9^o of flexion. This may be because of the stabilisation provided by the iliolumbar ligament (Fujiwara et al., 2000). Additionally, they (Cunningham et al., 2020) found extension range was inversely proportional to that of flexion. Combining and determining average ranges from selected papers in their literature review, Widmer et al. (2019) cited each lumbar motion segment's full sagittal, frontal and transverse plane's end-to-end movement. The greatest end range flexion to extension was 14.7^o at L4/5, followed by L5/S1 with 14.3^o; the least with a range of 9.9^o, was at L1/2. End-to-end range, left to right lateral flexion was greatest at L2/3 (11.4^o) and least at L5/S1 (5.2^o). Total left to right rotation was greatest at L5/S1 (5.6^o), followed closely by L4/5 (5.1^o) and least at L3/4 (4.3^o).

2.5.3 Lumbar Spine Intervertebral Disc Anatomy

An intervertebral disc consists of a nucleus pulposus surrounded by the annulus fibrosis. A normal annulus fibrosis consists of approximately 20 concentric lamellae (Vergroesen et al., 2015) - orientated vertically peripherally and becoming progressively more oblique towards the centre (Kapandji, 2009). These fibres, angled 25^{o} to the horizontal, resist distraction, shear and torsional forces (Neumann, 2017).

Diurnal water imbibition has an effect on spinal ROM. Compressive loading through the course of the day causes water to escape through microscopic pores in the vertebral end-plate leading to disc narrowing. During nocturnal recumbency, the disc's hydrophilic properties draw fluid back, causing the nucleus to regain its original shape. With aging, the ensuing decline of disc hydrostatic pressure causes loss of height and spinal flexibility (Kapandji, 2009).

2.5.4 Lumbar Spine Intervertebral Disc Biomechanics

Lumbar flexion results in posterior migration of the nucleus pulposus, with extension causing the opposite (Kapandji, 2009). Surprisingly, Berry et al. (2019) found that while the disc's anterior-posterior length diminished in end range sagittal positions, the height of the disc on the "compressed" side remained unchanged and increased on the opposite side. This suggested that distraction forces must be acting on healthy discs in end range flexion and extension. Technological limits prevented them from acertaining disc behaviour in rotation and lateral flexion.

Due to the alternating fibre pattern of succesive lamellae, half the fibres become tensioned with torsional stresses (Kapandji, 2009; Neumann, 2017). Axial rotation places a stretch on these oblique fibres, proportionally increasing the compressive forces on the nucleus puloposus with larger movements. This explains why combined lumbar flexion and rotation results in disc injury; it simultaneously increases the pressure on the nucleus and strains the fibres of the annulus (Kapandji, 2009).

As noted above, the greatest intersegmental flexion and rotation ranges occur at L4/5 and L5/S1 (Widmer et al., 2019). As these levels also contend with the largest compressive load, they predictably often present clinically. Circumferential annular tears occur with intersegmental rotational movements of greater than 3^{o} (Swanson and Creighton, 2020; Hadjipavlou et al., 2008; Mitchell Jr and Galen Mitchell, 2002). This becomes possible after facet injury or with combined flexed and rotated spinal positions when the articular processes gap, offering less protective restraint of movement (Hadjipavlou et al., 2008; Swanson and Creighton, 2020). Swanson and Creighton (2020) reported that instability from disc degenerative disease resulted in segmental rotation ranges of 4^{o} to 6.1^{o} and that combined movements of 7^{o} of flexion and less than 3^{o} of rotation caused annular strain.

Defined by Panjabi (1992), an intervertebral segment's neutral zone, is the portion of its physiological range commencing at neutral and ending where resistance to movement is first detected (Swanson and Creighton, 2020). While ROM is limited by skeletal and ligamentous structures, the neutral zone is controlled by the neuromuscular system (Swanson and Creighton, 2020). Reduced intradiscal pressure and axial compression causes increased shear forces on the disc, increasing the segment's neutral zone with lumbar flexion-extension (increasing anterior-posterior translation) (Panjabi, 1992) and rotation (Vergroesen et al., 2015). At certain vertebral levels (for example at L4/5 during flexion), pronounced angular movement occurs simultaneously with large translations, placing increased stresses on the disc. This may be the reason for commonly seen disc degeneration at these levels (Widmer et al., 2019). As the disc provides "intrinsic resistance to small spinal movements" an increase in the neutral zone is a more telling indicator of segmental instability than changes in ROM (Swanson and Creighton, 2020). In contrast, Tanaka et al. (2001) found that x, y and z-axial rotations were more sensitive to disc degeneration than segmental translations.

2.5.5 Pathological Lumbar Spine Intervertebral Disc Function

Disc degeneration sees a shift of nucleus pulposus' notochordol cells to chondrocyte-like cells (Vergroesen et al., 2015), leading to diminished proteoglycan synthesis and a transition from type II to type I collagen formation (Inoue and Espinoza Orías, 2011; Vergroesen et al., 2015). This may be caused by aging, genetic factors, diminished vascularity, smoking, metabolic disorders, low grade infection, neurogenic inflammation, autoimmune responses or mechanical factors (Hadjipavlou et al., 2008). The resulting loss of hydrostatic pressure and greater fibrosis causes a stiffening of the tissue, changing the load mechanics and ironically, making the disc more unstable (Inoue and Espinoza Orías, 2011). Creating a vicious cycle, as comparably seen in cartilage and bone tissue reacting to external loads, these shear stresses on the disc causes increased fibrous tissue production, rich in type I collagen (Vergroesen et al., 2015).

Stiffness of the nuclear tissue results in unequal and greater force concentration on the annulus (Swanson and Creighton, 2020). This altered disc loading creates torsional stresses. Additionally, decreased intradiscal pressure reduces tension in the annulus causing bulging of its layers and leading to increased shear forces between the laminae. The lamellae thicken and fibrillate, becoming more susceptible to shear stresses. With fissuring and cavity development, the resulting delamination leads to the formation of annulus tears (Hadjipavlou et al., 2008; Inoue and Espinoza Orías, 2011; Vergroesen et al., 2015). These tears precipitate an inflammatory response and a reduced concentration of proteoglycans. One of the inflammatory mediators, nerve growth factor, encourages nociceptive innervation into the outer two thirds of the annulus turning the disc pain sensitive (Swanson and Creighton, 2020).

Microscopic and macroscopic damage to the endplate with accompanying sclerosis of the subchondral bone precedes disc degeneration. This causes decompression of the nucleus pulposus and impairs disc nutrition (Vergroesen et al., 2015). Vertebral endplate damage can also result in lamellae buckling; compressive loads in turn cause delamination resulting in concentric annular tears (Hadjipavlou et al., 2008). Disc degeneration and endplate fractures do not only result from traumatic events, fatigue failure or repetitive “subliminal insults” can also have adverse effects (Hadjipavlou et al., 2008).

In vivo 3D computed tomography studies have revealed a direct correlation of the severity of disc degeneration with increasing segmental torsional instability (Inoue and Espinoza Orías, 2011). First proposed in 1982, Kirkaldy-Wallis and Farfan presented the idea that disc degeneration passes through three pathophysiological stages, namely, dysfunction, instability and stabilisation (Swanson and Creighton, 2020; Fujiwara et al., 2000). Degenerative disc disease and protrusion results in loss of disc height with spinal canal, lateral recess and intervertebral foramen narrowing. This narrowing leads to a 50% increase in compressive forces on the neural arch (Desmoulin et al., 2019). Disc disease thereby precedes facet joint OA (Fujiwara et al., 2000). Resultant slackening of the surrounding ligaments contributes to intersegmental instability, placing strain on the facet joints, causing apophyseal joint osteophyte formation and ligamentum flavum hypertrophy (Thomé et al., 2008). This OA with its cartilage degeneration and thinning may also produce capsular ligament laxity and segmental hypermobility (Fujiwara et al., 2000). Following these processes, consequent tendon laxity may reduce muscular control of the segment further enabling instability (Widmer et al., 2019). The segment’s axis of rotation migrates posteriorly, in severe cases pivoting the superior vertebra and transposing the axis onto the contralateral facet (Swanson and Creighton, 2020). Mitchell Jr and Galen Mitchell (2002) were of similar opinion, that after 2^{o} or 3^{o} of rotation an impacted apophyseal joint causes the segment to translate laterally, placing a shearing force on the intervertebral disc and in turn, gapping the ipsilateral facet.

Rather than being just a theoretical construct, the relationship of disc degenerative changes and motion segment instability has been investigated (Tanaka et al., 2001). They measured each mounted spinal motion segment’s (n=114; T12/L1 to L5/S1) translations and six physiological ranges with an optoelectronic motion capture system while subjecting them to increasing loads. Then using Thompson’s disc degeneration classification system (please see Appendix A for the complete description), they graded the upper (T12/L1 to L3/4) and lower (L4/5 and L5/S1) lumbar motion segments with MRI and cryomicrotome studies. Motion units with severe facet joint OA and tropism were excluded. They concluded that disc degeneration affects segmental mobility, having unique effects on each physiological range in the upper and lower lumbar spine. Increased general motion was seen in levels with degenerative discs and annular tears, specifically in those classified as grades III and IV. Intervertebral disc narrowing and osteophyte formation characteristic of grade V degeneration, resulted in segmental “stabilisation”.

In a similar study, also making use of Thompson’s disc degeneration classification system, research was conducted on the effects of disc degeneration and facet joint OA on motion segment mobility (Fujiwara et al., 2000). Using MRI, they graded 110 cadaveric motion segment’s disc and facet joint degeneration from T12/L1 to L5/S1. The facet joints were classified into four grades scored by the appearance of articular cartilage degeneration, subchondral bone sclerosis and osteophyte formation. The motion segments were then mounted and progressive loads into flexion/extension, lateral flexion and rotation were applied. Segmental movement was measured with a motion analysis system. In both genders, they identified a trend of increasing disc mobility with increasing degenerative severity up until grade IV but this movement decreased with grade V. Disc degeneration saw statistically significant increases in flexion, lateral flexion and rotation movement in men but only rotation ranges were significantly affected in women. Facet joint cartilage degeneration resulted in increased rotation range and reduced lateral flexion and flexion motion in the female spines. Male motion segments with grade III cartilage degeneration, exhibited increased mobility in all ROM but motion reduced however, with grade IV degeneration. Osteophyte formation did not have a significant effect on segmental movement but this association varied with diagnosis, seeing instability in degenerative spondylolistheses and hypomobility in spinal canal stenosis. Lastly, functional motion segments with bone sclerosis showed reduced mobility in both male and female spines. This was thought to be because of the associated degenerative changes in the capsular ligaments and ligamentum flavum rather than the sclerosis itself.

A recent systematic review on healthy and degengerative spinal kinematics was supportive these results above, concluding that the processes counteract eachother. That is, cartilage degeneration caused increased mobility which is tempered by osteophyte formation and subchondral sclerosis (Widmer et al. 2019).

2.6 Hip ROM

2.6.1 Normal Hip ROM Values

Normal hip ROM is limited by hip capsule restriction and osseous and soft tissue impingement of the labrum and capsule (Turley et al., 2013). In instances where both sides are impaired, a normal body of hip range measures is required for comparative purposes.

Two seminal guides on normal hip joint ROM are those of the AAOS, as quoted by Clarkson (2000), circulated in 1965 and Peterson Kendall et al. (1993) first published in 1949. The AAOS lists normal active hip ROM as follows: hip flexion: 0 - 120^o; extension: 0 - 30^o; abduction: 0 - 45^o; adduction: 0 – 30^o; IR: 0 – 45^o and ER: 0 – 45^o. More recent texts are still supportive of these values (Clarkson, 2000; Clarkson, 2013). Peterson Kendall et al. (1993) value's differ slightly - hip flexion, quoted as approximately 125^o, extension "about" 10^o, abduction 45^o and adduction 10^o.

Other authors who have published complete guides of hip ranges include, Roaas and Andersson (1982), whose mean findings comprise 120^o for flexion, 9.5^o for extension, 38.5^o for abduction, 30.5^o for adduction, 32.5^o for internal and 33.6^o for ER. Sahrmann's (2002) normal values stated hip flexion of 125^o, hip internal and ER to approximate 45^o, abduction 45^o and adduction 10^o. She offers normal hip extension as 10^o, but notes in individuals with a posterior pelvic tilt and hyperextended knees this would approach 20^o.

What will become apparent later in this literature review is that some of these standards, particularly those on rotation range, are in need of revision.

2.6.2 Effects of Age and Gender on Normal Hip Range Values

Age and gender's effects on tissue laxity and joint mobility may result in different joint ROM. Roach and Miles (1991) looked at the effect of age on active hip ROM. Examining people from the age of 25 to 74, they found that only hip extension diminished by a clinically significant 15% (or more) from the youngest to the oldest group. They explained this may be because extension, of all hip movements, has the smallest range and would have most likely been affected by their approach of rounding measures to the nearest 5^{o}. They did however conclude that any considerable loss of range up until the age of 74 is abnormal and should not be accredited to ageing.

Women have a significantly greater amount of active hip internal and ER (Simoneau et al., 1998) and greater hip flexion (Beneck et al., 2018) than men. Similar results were obtained in a study of 339 sportspersons, finding women had greater IR range but similar ER range to men (Hogg et al., 2018). Surprisingly, this is not true of all ranges. Women have been found to have significantly diminished hip extension range, anterior pelvic tilt compensating appreciably for the deficit (Beneck et al., 2018).

2.7 Anatomical Factors Affecting Hip Range Outcomes

2.7.1 Anatomical Factors Affecting Hip Flexion and Extension Outcomes

Skeletal morphology is an important determinant of sagittal range. Femoral and acetabular version have been shown to affect hip flexion ROM. Hips with combined femoral and acetabular anteversion demonstrated the greatest range, while those with femoral anteversion and acetabular retroversion displayed the least (Chadayammuri et al., 2016).

Controlling pelvic tilt position poses a challenge when measuring hip range in the sagittal plane. Textbooks do not adequately define pelvic start and end position during hip flexion and extension (Beneck et al., 2018). Testing hip flexion with the contralateral hip in full flexion, enabling posterior pelvic tilt and lumbar flexion, may exaggerate the range. Making use of this position, a group of men between 30 and 40 years of age achieved an upper limit of 150º, although still deriving a mean of 120º (Roaas and Andersson, 1982). This concern is resolved to some degree, by placing the contralateral hip in neutral and using ipsilateral hip joint end-feel or palpation to sense lordotic flattening on the test side (Beneck et al., 2018).

Accurate prone hip extension measurement, on the other hand, is more challenging. Identifying a neutral spine starting position is problematic. Palpation to determine intersegmental neutral is demanding, complicated by erector spine muscle activity. Undoubtedly, there would be debate on which spinal level to use. Furthermore, having to control and determine the amount of compensatory anterior pelvic tilt during the hip extension testing procedure is difficult. This all may explain hip extension's wide range of normal values, varying from 10º to 30º (Van Dillen et al., 2000). In light of these challenges, to ensure greater accuracy of results and contrary to earlier guidelines (Clarkson, 2000), this researcher adopted a prone position, without a pillow under the abdomen. Having a pillow in position may have prevented compensatory lumbar extension, but it would have also increased the starting position's hip flexion angle, exaggerating the hip extension range.

Beneck et al. (2018) measured the contribution of pelvic tilt to these ranges through a rigid device fixed to the anterior and posterior superior iliac spines. They considered hip flexion in supine and extension using the Modified Thomas Test (MTT). The change in pelvic tilt, namely the difference of pelvic angle between end range flexion and extension from what had been predetermined in standing, was deducted from the hip range. During hip flexion, posterior pelvic tilt accounted for 17º of the range in men and 14º in women. During hip extension, anterior pelvic tilt accounted for 0.2º of the range in men and 9.3º in women - they attributed this to increased hip extensor flexibility on the contralateral side in women. This confirmed their hypothesis that pelvic rotation should be distinguished and corrected for when measuring hip flexion and extension. They concluded that to avert this problem, pelvic tilt should be corrected in both genders during hip flexion and in women when using the MTT (or alternatively, female's anterior superior iliac spines (ASIS) should be stabilised during this procedure).

Using this approach discerns the extension range provided by the pelvic tilt and hip joint extension. Once greater normative data is available, the clinician could identify whether the lumbar spine or hip's hyper- or hypomobility is at fault and direct treatment accordingly. One oversight is that they (Beneck et al., 2018) performed the MTT with the knee in flexion; this would have allowed the tensor fascia lata, rectus femoris and/or sartorius to influence their results as they did not seem to be monitoring knee angle (Peterson Kendall et al., 1993; Sahrmann, 2002). A solution may be to combine their methodology with Van Dillen et al.'s (2000), who performed the MTT in knee extension, obtaining a clearer picture of the one-joint hip flexors' length. This methodological combination is impractical though, requiring two clinicians to perform the test with an IMU and three people when using a goniometer.

These testing nuances generate varying results. Hip flexion, incorporating the joint movement and posterior pelvic tilt, was found to be a mean of 110.8º in men and 121.3º in women (Beneck et al., 2018). Klassbo et al. (2003) tested passive hip flexion with a goniometer in a population without OA and average age of 58.6 years, obtained a mean of 122º for hip flexion. Prather et al. (2010) also testing passive hip range in asymptomatic participants, derived a mean of 111.25º for hip flexion and 17.05º for extension in prone with goniometer.

2.7.2 Anatomical Factors Affecting MTT Range Outcomes

Although the MTT position is used at times to measure hip extension, in this study, it was incorporated to improve the accuracy of SLR outcomes (this is detailed below). Poor reliability (Paatelma et al., 2009) and non-standardised execution has lead to a wide range of normal values.

The Thomas and MTTs are beset with problems due to poor standardisation and because their technique is difficult to control. The original Thomas Test positions a person supine with the test thigh lowered onto the plinth surface. In contrast, the MTT places the participant at the bottom edge of the plinth, thereby allowing the test thigh to drop below the horizontal (Lifshitz et al., 2020). The starting position is then identified by palpating for the lumbar spine's flattening against the plinth surface as both of the participant's flexed knees are moved toward their chest (Clapis, Mercik Davis and Davis, 2008; Klassbo, Harms-Ringdahl and Larsson, 2003; Beneck et al., 2018). This suggests that the spine is flexed and accompanied by a posterior pelvic tilt, where a neutral spine would be the desired position (Beneck et al., 2018). A further problem is that the positioning is not standardised, with some researchers' participants pulling the contralateral thigh against the chest (Roach et al., 2013). In this circumstance, excessive hip and thereby lumbar flexion, would see a falsely diminished hip extension range. This for example, may explain Roach et al.'s (2013) low goniometric mean values, 3.4^{o} for the left hip and 4^{o} on the right

Another occasionally neglected consideration is the effect tensor fascia lata, rectus femoris and/or sartorius tightness could have on Thomas test outcomes (Peterson Kendall, et al., 1993; Sahrmann, 2002). Echoing all these concerns, Abady Avman, et al. (2019) noted the Thomas and MTT's poor validity in the measurement of hip extension, particularly in those with non-specific lower back pain. Taking a unique approach, Van Dillen et al. (2000) adapted the MTT. By performing the test with knee extension, they negated the effects of the two-joint hip flexors on hip extension range. Together three examiners conducted the test. The first palpated the lumbar spine, assessing for lumbar extension as the test hip was lowered into extension, the second held the test side knee in extension and the third took the goniometric readings. Using this method, their asymptomatic group had a mean of 11.43^{o} and back pain group 12.6^{o} of hip flexion, when the hip was in 0^{o} abduction and knee flexed 80^{o}. With the hip in 0^{o} abduction and knee extended, the control and lumbar pain groups exhibited means of 2.49^{o} and 6.65^{o} hip flexion, respectively.

Other results for the MTT, included 10^{o} of extension in a cohort of non-osteoarthritic hips (Klassbo et al., 2003) and means of 14.7^{o} extension in men and of 15.5^{o} in women in an asymptomatic sample (Beneck et al., 2018).

2.7.3 Anatomical Factors Affecting SLR Range Outcomes

One intention of this study was to determine the effect of hamstring length on lumbar flexion symptoms. Contralateral one-joint hip flexor length has a bearing on the ipsilateral SLR range, consequently, the MTT was required to assess these muscles.

On lifting a leg for testing, a shortened contralateral hip flexor pulls the pelvis into an anterior tilt position. This causes the ipsilateral ischium to slide in a cephalad direction, separating hamstring muscle origin and insertion and thereby deceptively creating the appearance of a tighter hamstring (Peterson Kendall et al., 1993). On identifying a short contralateral iliopsoas with the MTT, the author, following Peterson Kendall et al.'s (1993) guidlines, added the tight (positive) hip flexor's range amount to the ipsilateral SLR's range to ensure greater accuracy. Additionally, the contralateral thigh was tied down to the plinth to prevent excessive and undesirable pelvic rotation (Peterson Kendall et al., 1993). At end range, the raised test leg pulls the ipsilateral ischium caudad, creating a posterior pelvic tilt and falsely increasing the test leg hamstring's range. This pelvic rotation is countered by the contralateral hip flexors, holding the opposite side in an anterior pelvic tilt. Although in this author's opinion, presumably and conversely, a long contralateral hip flexor would allow excessive ipsilateral posterior pelvic tilt at the end of (SLR testing) range giving the illusion of a flexible hamstring.

Keeping the test side in 0° abduction after extending the knee during MTT assessment is believed to bias the anterior fibres of gluteus medius instead of iliopsoas (Van Dillen et al., 2000). To get a true indication of iliopsoas length and diminish tensor fascia lata and rectus femoris' effect, it was advised to extend the knee with the hip in abduction (Van Dillen et al., 2000; Sahrmann, 2002). Although this may have been preferred, it was not adopted, as SLR is tested in 0° abduction: any one of the one-joint hip flexor muscle's influence would have needed to be identified during testing and addressed with the calculation.

Hamstring length testing in the 90° hip flexion position was not adopted because normal values for the muscle's length are largely quoted using the knee extended position (see below); the knee extended position affords greater control during the testing procedure and as per the study's fifth objective, assessing whether symptomatic lumbar flexion is associated with altered SLR ROM, the physiological lumbar movement is performed with the knee extended. Furthermore, the effects of neural tension were minimised by allowing the participant's foot to fall into plantarflexion during testing.

Normal hamstring length is defined as an angle of approximately 80° (Peterson Kendall, et al. 1993). Using a small sample size, Halbertsma et al. (2001) found normal SLR values, in an asymptomatic sample, to range from 69.73° to 88.7°; asymptomatic "flexible" individuals had a mean of 84.4°, while asymptomatic "stiff" participants displayed a mean of 77.2°; the mean range in the symptomatic group was 66.5°. They unfortunately didn't compare side-to-side ROM. Using a larger, 47 participant, asymptomatic sample, Gugliotti et al. (2018) found a mean SLR of 81° and 80° for left and right leg respectively. Johnson and Thomas' (2010) pain-free group showed similar values, with a mean SLR range of 80.7° on the right and 77.2° on the left.

2.7.4 Anatomical Factors Affecting Hip Abduction and Adduction Range Outcomes

Coxa valgum and varum, an abnormal femoral neck angle of inclination, is a bony abnormality which affects hip abduction and adduction range. This is the angle of the femoral neck relative to the femoral shaft in the frontal plane; normal is about 125^{o}, an angle less than 120^{o} is termed coxa vara, while an angle greater than 130^{o} is designated coxa valga (Neumann, 2017; Sahrmann, 2002). Individuals with coxa vara have limited hip abduction and IR (Anon., 2021), while those with coxa valga present with reduced adduction (Tubby, 1908). The degree of femoral and acetabular version has been shown not to affect abduction ROM (Chadayammuri et al., 2016).

Previous research found mean passive hip abduction to be 27^{o} and adduction 28^{o} (Klassbo et al., 2003). Prather et al. (2010) also testing passive hip range in asymptomatic participants, found a mean of 40^{o} for hip abduction and 12.35^{o} for adduction with a goniometer.

2.7.5 Anatomical Factors Affecting Hip Internal and ER Range Outcomes

Bony architecture is a determinant of hip ROM. Femoral neck torsions, namely anteversion and retroversion, a rotation of the femoral shaft about the femoral neck impacts on hip rotation range. Similarly, acetabular angulation also varies and it too plays a related role. Combined femoral and acetabular anteversion, sees excessive hip IR and diminished ER, while combined femoral and acetabular retroversion causes excessive hip ER and limited IR (Sahrmann, 2002; Chadayammuri et al., 2016). In a study of 538 symptomatic hips, Lerch et al., (2018) found 6% displayed femoral and acetabular anteversion; 4% exhibited femoral and acetabular retroversion and 32% demonstrated normal femoral and acetabular version. The most common abnormality, seen in 22% of their cohort, was normal acetabular version with femoral anteversion. Femoral anterversion is associated with hip dysplasia, pincer FAI(FAI) and cerebral palsy; while femoral retroversion, is associated with cam FAI and slipped capital femoral epiphysis; acetabular anteversion is seen in hip dysplasia and lastly, acetabular retroversion is associated with femoral head osteonecrosis and Legg-Calve-Perthe's disease (Chadayammuri et al., 2016). Furthermore, increased and decreased femoral version has also been linked to hip OA and labral tears (Cibulka, 2004). Passive hip rotation testing significantly predicts whether these biomechanical conditions are present (Cibulka, 2004; Chadayammuri et al., 2016). Although sagittal hip position plays a role, adults with differences of greater than 20º between their hip IR and ER ROM are believed to have a femoral version abnormality (Uding et al., 2019).

The AAOS guidelines state normal hip internal and ER ranges of 45º. In contrast, using goniometer and inclinometer, a former study identified four patterns of hip rotation ROM in a sample of 150 people (Ellison et al., 1990). Pattern IA where left and right total IR was symmetrically equal to total ER; pattern IB where total IR was asymmetrically equal to total ER; pattern II, where total IR was greater than total ER and lastly, pattern III, where total ER was greater than total IR. Of interest, only 27% of their population met the AAOS standard of equal internal and ER range, with 27%, 5%, 41% and 27% of asymptomatic lumbar participants, respectively, presenting with pattern IA, IB, II and III. Kouyoumdjian et al. (2011) found that 39.5% of the hips they studied had equal internal and ER range, but in contrast, 47.5% of their group had a predominance of ER, and the remaining 13% had a prevalence for IR. In their systematic review, Abady Avman et al. (2019), note emerging evidence of an association between femoral anteversion and non-specific low back pain. They conclude that further research is necessary to determine whether hip ROM is a compensatory mechanism for variation of femoral and acetabular version.

Previous rotation range results have varied not only because of the anatomical features discussed above but also because of testing positions and techniques used. McCulloch et al. (2014) found that hip IR range varied from 23.9º to 41.3º; ER from 23.5º to 45.3º, with the total arc of rotation ranging from 53.3º to 79.1º. Simoneau et al. (1998) reported mean active hip ER, in 90º hip flexion, as 36º ± 7º and 45º ± 10º in prone, while mean active IR in sitting was 33º ± 7º and prone 36º ± 9º. Roach et al.

(2013) got mean values of 37.5º for passive IR with goniometer and 33.2º with inclinometer. Their mean passive ER values were admittedly high of 54.5º and 55.5º for inclinometer and goniometer respectively. Klassbo et al. (2003) testing passive hip rotation in a non-arthritic sample with a mean age of 58.6 years, in prone with a goniometer, obtained a mean of 34º and 28º for internal and ER respectively. Finally, Prather et al. (2010) measured passive hip rotation with a goniometer in prone and in supine with the hip flexed to 90º. Their results showed a mean of 29º for IR and 48º for ER with hip flexed 90° in supine and 31.38º for internal and 40.4º for ER in prone.

2.8 Hip ROM Side-To-Side Asymmetries

Research-based confirmation of hip side-to-side range symmetry reassures the clinician in setting treatment goals after unilateral injury (Hogg et al., 2018). As the reader will see below, the bulk of previous research has focussed on hip rotation asymmetries - other ranges have received limited attention.

A number of studies have found no significant side-to-side hip rotation differences. Testing active and passive hip rotation in prone, sitting, and a neutral weight-bearing position in an asymptomatic, pathology-free cohort (average age 27.1 years) Aefsky et al. (2016) found no side-to-side differences across all three positions. Similarly, using a goniometer and inclinometer, Roach et al. (2013) measured passive internal and ER in prone in a healthy population with a mean age of 34 years. They too found no significant differences between sides. Young et al. (2014) not stating whether they were measuring active or passive hip rotation, came to the same conclusions. Namely, they found no difference between dominant and non-dominant leg hip internal and ER in 0º and 90º hip flexion in a female professional tennis player group. Although testing active movement, comparable results were attained by Ellenbecker et al. (2007), who found no clinically significant internal and ER side-to-side difference in tennis and baseball players. However, they did find the tennis players displayed a statistically significant 2.5º side difference in total hip rotation.

In contrast, McCulloch et al. (2014) found significant passive hip rotation side-to-side differences in professional baseball pitchers. These disparities were more evident in their older participants. This, they concluded, in keeping with lower quarter pitching biomechanics, was due to adaptive mechanisms. Hogg et al. (2018) researched prone hip rotation, in 20º to 30º abduction to minimise muscular effects, in a large group of multidisciplinary collegiate athletes with a mean age of 19.3 years. They found substantial side-to-side differences, where 32% of their participants exceeded a 6.8º, 7.4º and 6.2º left-right discrepancy in IR, ER and total rotation, respectively. Five percent of their population had respective side differences of greater than 13.4º, 14.5º and 12.1º.

More comprehensive studies considering the full spectrum of hip range's side-to-side asymmetries have had mixed results. Roaas and Andersson (1982) researched an asymptomatic lumbar sample of men aged 30 to 40, without history of lower limb disease and trauma. Testing all passive hip ranges and rotation in prone, they found no significant side-to-side differences. More recently, using inclinometry and goniometry, Moreno-Perez et al. (2016) looked at variations in passive hip side-to-side flexion, extension, abduction, prone internal and ER ROM in elite tennis players. Male (mean age 19.7 years) and female (mean age 17.7 years) volunteers were excluded if they suffered an orthopaedic problem in the previous three months. It should be noted that they measured hip extension using the Thomas test and, surprisingly, named hip flexion as such, but were in reality measuring SLR. They found there was a statistically significant difference between sides for passive hip "flexion" and abduction in both sexes and in IR in men. They however, did not deem their results clinically significant as the measurements were lower than a proposed 10º threshold. They found as little as 14% of participants showed a hip side-to-side difference of greater than 10º.

Studies investigating SLR range asymmetries have also had varied results. Gugliotti et al. (2018) using a 47 participant asymptomatic sample, with an average age of 49.9 years, found a mean range of 81º and 80º for left and right leg respectively. The contralateral side was not bound down but they did control neural tension. There was no significant side-to-side difference. Johnson and Thomas' (2010) performed a retrospective analysis of data from previous SLR studies in healthy individuals recovering from lumbar pain and low back pain groups. The pain-free group, consisting of 18 participants with a mean age of 23.8 years, showed a mean SLR range of 80.7º on the right and 77.2º on the left, unfortunately they did not comment on whether this was a significant side-to-side difference.

Evidently, further studies are required investigating hip flexion, extension, abduction and particularly adduction side-to-side discrepancies. Echoing this opinion, a systematic review recently concluded that further research is required exploring asymmetries in all hip ROM to determine whether there's an association with lower back pain (Abady Avman et al., 2019). This study would add to that body of knowledge.

2.9 The Effects of Hip Flexion Position on Hip Rotation Range

As outlined above, the lumbar spine is often injured in combined flexion and rotation. Combined hip flexion and rotation contribute motion to this position. Determining whether sagittal plane positioning affects hip rotation range may inform opinion on mechanisms of injury and guide manual treatment, exercise prescription and patient education. In this interest, rotation range in the 0º, 30º and 90º sagittal plane positions was explored in this study. As set out below, numerous studies have examined the neutral and 90º hip flexion positions, but to the author's knowledge, there is no research into the 30º position. This may be because of technological obstacles or possibly through the belief that mid-range, loose-pack hip positions do not limit range.

Generally, most studies have found no significant rotation range differences between the 0º and 90º positions. Not stating whether they measured active or passive movement, Young et al. (2014) assessed hip rotation in prone and sitting, in 125 professional female tennis players with a mean age of 24.7 years, using a digital inclinometer. They found no significant difference for external and IR between the two postural positions. Similarly, Ellison, Rose and Sahrmann (1990) did their research reliability testing on 22 healthy volunteers. Using a goniometer and inclinometer they assessed passive hip rotation in prone and sitting. They found no significant difference between the two position's results. In a unique study, Kouyoumdjian et al. (2011) also performing passive rotation, compared the range in prone, supine and sitting. Their population, with mean age of 39.1 years, consisted of 120 men and women without hip, spinal or lower limb conditions. They found these contrasting hip flexion positions had no significant effect on rotation range.

The above findings were not ubiquitous, although these opposing conclusions seem to predominant in studies that tested active rotation in the different sagittal positions. In another unique study considering the effect of prone, seated and a loaded, half-kneeling position on hip rotation range, Aefsky et al. (2016), making use of a goniometer and cervical ROM compass on 20 healthy participants (mean age 27.8 years) found active internal and ER diminished significantly with each of the respective positions above. Passive ER was also significantly less in sitting when compared to the prone position, while passive IR showed no significant change between the three positions. With some similarity, Simoneau, et al. (1998) compared active hip rotation range in 60 healthy volunteers, with an average age of 21.8 years, in the seated and prone positions. They found active hip ER was significantly greater in the prone position when compared to sitting, although active hip IR showed no significant difference between the positions. In light of the passive testing results above, these findings may be indicative of the effects of gravity and strength rather than the effects of differing testing positions, that is, gravity-assisted active prone measurements were realistically greater than gravity-bearing sitting ones.

2.10 The Association between Lumbar Pain and Hip Range Mobility

The hip plays an integral part in generating and transferring force through the kinetic chain. It enables greater power to be transmitted from leg to hand, but due to the hip and lumbar spine's close anatomical proximity a dysfunctional hip joint can result in increased stresses on the lower back precipitating injury (Young et al., 2014). Numerous studies have examined the relationship of hip joint range and lumbar symptoms, although criticised for their low overall quality of evidence due to small sample sizes, blinding of researchers, adjustment for confounders and poor reporting (Abady Avman et al., 2019).

2.10.1 Hip Flexion Range Associated with Lumbar Pain

Diminished hip flexion range fosters greater movement demands from the lumbar spine during daily activities such as dressing, rising from a chair and squatting. Hip flexion, extension and abduction ranges were explored through goniometric measurements in presumably symptomatic, hip osteoarthritic participants ($\bar{X}$ = 63.3 years) with (n = 18) and without (n = 17) low back pain (Tanaka et al., 2015). They did not state whether these movements were performed actively or passively nor were there any specifics on their measurement methodology. The low back pain group displayed a significantly reduced hip flexion range with a "marginally significant" increased abduction range on the degenerative side. They believed that the observed increased abduction range was compensating for the reduced hip flexion motion during activities of daily living. In a similar study, French et al. (2015) examined active hip flexion, abduction, internal and ER (in sitting) with a goniometer in symptomatic hip osteoarthritic patients presenting with and without lower back pain. Comparably, the mean age of their 24 participants, was 65. Although all the tested ranges were reduced in the affected hip in the low back pain group, only hip flexion displayed a significantly decreased range.

Rather than being a research aberration, differing cultural practices could be the reason for the different hip abduction range findings in the above two studies. Tanaka et al. (2015) having studied Japanese participants, who may have readily sat cross-legged on the floor, found an increased compensatory abduction range, while French, et al. (2015) testing an Irish population, who were likely to have sat on conventional chairs, seemly made no such observation.

For comparative purposes, as this study researched a younger cohort ($\bar{X}$ = 47.39 years) without any hip disease, Adegoke and Fapojuwo (2010) measured active hip flexion with a goniometer in 30 lower back pain and 30 male control participants. In a similar vein, their control group had significantly more active left hip flexion than their lower back pain group.

These findings are not widespread across the literature though, Tsai et al. (2010) examined active hip flexion, extension, abduction, adduction, internal and ER ROM in golfers with and without a history of lumbar pain with a standard goniometer. They omitted details of their methodology. Their smaller groups, 16 volunteers in each, with a similar mean age of 48.25 years to that of the study above, had contrasting results. They found no significant difference between their groups for all these hip ROM.

2.10.2 Hip Extension Range Associated with Lumbar Pain

Although a number of studies exist exploring the association of hip extension and lumbar pain, they are hindered by small sample sizes and differing methodologies. As detailed in paragraph 2.10.1 above, Tanaka et al. (2015) measured a total of 35 participants' hip extension range. Extension was assessed goniometrically in prone, but participants who could not tolerate this neutral position were moved into side-lying. No significant difference was found in the hip extension range across the two groups. With particulars also discussed in paragraph 2.10.1 above, Tsai et al's. (2010) study also found no significant difference in hip extension range between their small groups.

While making use of a fitting cohort size, Adegoke and Fapojuwo's (2010) methodology beggared further questions. They measured the active hip extension of their lower back pain (n = 30) and control (n = 30) male participants with a goniometer, in supine. Their outcomes were also weakened by only performing a single measurement - they too found no significant difference between their two groups' hip extension range.

An older study produced an opposite result, although again beset by small group sizes (Ashmen et al., 1996). In total, 16 female athletes', with and without chronic lower back pain, active hip extension was assessed in prone. In spite of their small sample size and a young cohort with mean age of 19, they found a significantly reduced left hip extension range in the experimental group. Considering the age of their population and the fact that they measured active movement, this author wonders whether these results were once again attributable to joint stiffness or rather non-dominant side weakness.

2.10.3 Thomas Test Range Associated with Lumbar Pain

Although incorporated here for the purposes of enhancing SLR assessment accuracy, the MTT's evaluation of iliopsoas shortening and its association with low back pain, is of value in an increasingly sedentary global population. As discussed below, the relationship of hip flexor muscle length with lumbar symptoms remains unclear.

Handrakis et al. (2012) measured hip flexor length, with a goniometer, using the MTT, dividing 84 college-age students (of average age 24.4 years) into minimal/ no lumbar pain and a low back pain groups. Holding the knee close to the chest with the contralateral limb over the bottom edge of the bed, they found no significant difference for the range between their groups. Equally making use of the MTT, Stuelcken et al. (2008) measured the range with a goniometer (with an attached spirit level for horizontal reference) in elite female cricket fast bowlers (of mean age 22.5 years) with (n = 14) and without (n=12) a history of lower back pain. Limited by difficulties finding a suitable sample size which affected the statistical power of their study, they found no significant difference between their lumbar pain and control groups.

Diverging, other researchers have found an association between these two variables. Roach et al. (2015) made use of the MTT and an inclinometer to measure hip extension in 30 control participants (mean age 34.0 years) and 30 experimental participants with a diagnosis of non-specific lower back pain (mean age 45.0 years). The contralateral leg was held against the chest with the test leg suspended over the bottom of the plinth. Although performed across both groups, this position would have placed the pelvis in a posterior tilt and not in neutral as they maintained. Their non-age matched control group had a significantly greater range than the lumbar pain group. Paatelma et al. (2009) assessed hip flexor length in 155 participants (with average age of 41.5 years), namely 55 control, 55 chronic low back pain and 47 subacute low back pain participants. They did not state their methodology. Even though they showed a significant difference between the control and subacute and chronic lumbar pain group's iliopsoas length, they questioned the accuracy of their result because of the test's poor reliability.

Lastly, in unique study, Van Dillen et al. (2000) researched the effect of hip and knee position on hip extension range using a derivation of the MTT. Thirty five asymptomatic (of mean age 31.37 years) and 10 participants (mean age 33.7 years) with low back pain were placed at the bottom of the plinth and their hip extension assessed with a goniometer in four different positions. Namely, hip extension range was measured in 0^o and full hip abduction with the knee at 0^o and 80^o knee flexion. Overall, the symptomatic group had significantly less hip extension than the control group. Both groups achieved more hip extension when the knee was extended and when the hip was abducted. The two-joint hip flexors behaved differently, tensor fascia lata limiting hip extension in both groups, while rectus femoris only affected the range in the symptomatic group.

2.10.4 Hamstring Length Range Associated with Lumbar Pain

A systematic review of lower back pain risk factors found that a reduced lumbar lordosis, diminished hamstring flexibility, and decreased lateral flexion ROM had a significant influence on its development (Sadler et al., 2017). In full lumbar flexion, erector spinae activity is silent, the spine supported by passive stretch of the muscle and ligaments (Esola et al., 1996). Normal lumbopelvic rhythm, sees hip extension followed by lumbar extension on return to the neutral position. A delay in the lumbar extension timing was observed when the spine was placed under load. Reduced hamstring flexibility, creating a compensatory hyperflexion of the lumbar spine in the bent forward position, also caused a delay in lumbar extensor contraction. This period of instability exposed the posterior ligaments and intervertebral discs to injury (Iwasaki et al., 2014). Despite this evidence, there are however, conflicting reports on the relationship of SLR range and lower back pain.

Halbertsma et al. (2001) measuring passive SLR found a significant difference in hamstring ROM between their control (n = 20; average age 28.8 years) and non-specific low back pain group (n=20; average age 33.0 years). They attributed the decreased range in the pain group to reduced stretch tolerance rather than muscle stiffness. Johnson and Thomas (2010) conducted a retrospective analysis of data from two earlier studies (study one with 86 participants and mean age of 30.9; study two consisted of 36 participants with mean age of 23). Evaluating SLR, not stating whether this was performed actively or passsively, they also found hamstring length was significantly less in people with lower back pain.

In contrast, Handrakis et al. (2012) evaluated hamstring length in collegiate students (total n = 84; average age was 24.4 years) using the passive knee extension test. Participants were positioned supine with the hip fixed in 90º flexion and then the knee was passively extended. They found no significant difference in hamstring length between their groups with low back pain or no/minimal low back pain. Using the same test but performing it actively, Reis and Macedo (2015) found reduced hamstring length in their chronic low back pain group (n= 36; average age 28.9 years) but it was not significantly different to their control group (n= 32; average age 25.95 years). Esola et al. (1996) researched participants with (n = 20, mean age 29.7 years) and without (n = 21; mean age 27.5 years) a history of low back pain; using the active knee extension and passive SLR tests, reached the same conclusion. Namely, there was a “trend” toward reduced flexibility in historically symptomatic participants but no significant difference.

All three studies (Halbertsma et al., 2001; Johnson and Thomas, 2010; Esola et al., 1996) showed lumbar spine flexibility to be no different between the pain and control groups. This lead Johnson and Thomas (2010) to conclude that the sequencing of lumbar movement may be a deciding factor in the development of lower back pain rather than its relative flexibility. Individuals with a history of low back pain have been shown to utilise their available lumbar range earlier in the bending motion range than historically asymptomatic individuals (Esola et al., 1996).

2.10.5 Hip Rotation Range Associated with Lumbar Pain

Without sufficient explanation, the greatest number of studies seeking a link between lumbar pain and hip ROM has been performed on hip rotation. This interest maybe because of the lumbar spine’s common rotatory mechanism of injury or because in order to achieve adequate, functional, physiological rotation range, the normally limited lumbar spine, requires the coupling of full hip rotation. Consequently, the absence of normal hip rotation has been believed to place stress on the lumbar tissues (Van Dillen et al., 2008). The differing hip rotation characteristics and their relationship with lower back pain is discussed below.

Examining whether a history of lumbar pain is associated with hip rotation deficits, Young et al. (2014) assessed 125 professional female tennis players’ (of average age 24.7 years) hip internal and ER in the seated and prone positions using an inclinometer. They collated each player’s subjective musculoskeletal history and a database of their injuries and then compared this to the clinical assessment findings. Eighteen percent of the players had suffered hip injury or surgery. Failing to report whether the testing was performed actively or pasively, no significant difference was found between the hip internal and ER range on the dominant and non-dominant sides of players with and without a history of lumbar pain. They speculated that this could be because they investigated a female cohort only. As detailed earlier, French et al. (2015) examined hip rotation range in an older population, of average age 65, all presenting with symptomatic, hip OA and absent or existing lower back pain. Active internal and external range was measured in sitting with a goniometer. Surprisingly, no significant difference in hip rotation range was found between the groups.

Presenting a differing opinion, Van Dillen et al. (2008) examined 48 athletes (24 with and 24 without lumbar pain) participating in rotation demanding sports. All but one participant was right-handed. With a mean age of 26.57 years, the participants had their passive hip rotation measured in prone using an inclinometer. They found significantly less total rotation, with asymmetrically less total left hip rotation than total right rotation in the symptomatic group. This result was observed in both genders. Their finding was substantiated by Mellin (1990) who measured active hip rotation with an inclinometer in the prone position, in 103 participants, 55 men and 48 women, of average age 21.4 years. Participants were grouped into those with a history of lumbar pain over the past year (n=55) and those who had never experienced lower back pain or had been pain-free over the previous 12 months (n=48). ER was significantly reduced in the symptomatic female group.

Rotation range side differences may also have an impact on low back symptoms, Vad et al. (2004) researched the IR range of 42 male professional golfers (average age 31) with (n=14) and without (n=28) a history of lower back pain. Methodological details were scant. Although IR range was performed with a goniometer, they took the unusual step of assessing ER using the FABER position. A significantly diminished difference was found between the lead and non-lead leg’s internal and ER range in the symptomatic group, this was not the case in the asymptomatic group. The side difference’s relationship with low back pain was corroborated by Murray et al., (2009), who obtained similar findings in 64 amateur golfers, 43 men and 21 women.

Individuals with current or a history of lumbar pain in the preceding year were placed in the experimental group (n=28), while the asymptomatic players over that period comprised the control group (n=36). The average age of the lower back pain and control group was 56.4 and 54.3 years respectively. Participants performed a 5 minute warm-up on a static bike before testing, where passive and active internal and ER measurement took place in prone with an inclinometer. The lumbar pain group's lead leg had significantly reduced active and passive IR compared to the control's and this range was also reduced in the symptomatic group's lead leg when compared to their non-lead side.

As mentioned earlier, exploring whether different hip rotation patterns have an association with lower back pain, Ellison et al. (1990) assessed hip rotation in 100 healthy volunteers (mean age 26) and 50 participants with lumbar symptoms and a variety of diagnoses (average age 37.4 years). Passive internal and ER range was measured with an inclinometer in prone. Based on the resulting hip angulation pattern they displayed, participants were further categorised into four different sub-groups. Although there was no significant difference between the two main groups' hip rotation ROM, the hip retroversion sub-group pattern was significantly prevalent in symptomatic individuals. Hip anteversion was the most dominant pattern in the asymptomatic volunteers.

2.10.6 Hip Abduction Range Associated with Lumbar Pain

Detailed in the paragraphs above, Adegoke and Fapojuwo (2010), French et al. (2015), Tsai et al. (2010) and Tanaka et al. (2015) studied the relationship of hip abduction range with lower back pain. To summarise, Adegoke and Fapojuwo (2010), French et al. (2015), Tsai et al. (2010) all found no significant difference between their groups, while Tanaka et al. (2015) were of the belief that the increased observed abduction range in the osteoarthritic side may have been a compensation for reduced hip flexion.

In essence similar to the papers above, but defined as a study on muscle length, Nourbakhsh and Arab (2002) researched passive hip adductor muscle length in a substantial sample of men and women with (n=300) and without (n=300) lower back pain. Using a goniometer centered over the pubic symphysis and palpating for pelvic motion, they measured the angle between the midline and the abducted longitudinal axis of the femur. They too, found no significant difference between the symptomatic and asymptomatic groups.

2.10.7 Hip Adduction Range Associated With Lumbar Pain

There appears to be a lack of research exploring the effect of hip adduction range on lower back pain (Abady Avman et al., 2019). This study would add to the body of knowledge.

Their sample outlined in paragraph 2.10.2 above, Adegoke and Fapojuwo (2010) compared active adduction range in low back pain and control groups with a goniometer. They did not detail their methodology but found no significant difference between the two groups. Similarly, Tsai et al's. (2010) research, also described above, found no significant difference between the active adduction range in their groups with and without a history of lower back pain.

2.11 The Beighton Scale

The Beighton scale was used to determine whether joint mobility was equivalent across the two groups. Beighton scores have been found to be predictive of hip capsular thickness; higher scores (≥ 4) were significantly associated with thinner capsules (Devitt et al., 2017). Based on the recommendations of a recent systematic review, a Beighton Scale score of ≥ 5 out of 9 was used as the defining hypermobility indicator in this study for its adult population (Juul-Kristensen et al., 2017). This was in line with Beighton et al.'s original guidlines (Russek and Errico, 2016).

Joint flexibility is affected by sex, age and ethnicity (Singh et al., 2017). Making use of the AAOS' proposed two standard deviations outside the mean joint ROM limit, Singh et al. (2017) researched Generalised Joint Hypermobility's prevalence in an ethnically diverse Australian population. Using one thousand participants, they identified the following Beighton scores for men and women in different age groups that corresponded to this 5% threshold: in females ≥ 6 in those aged 3 - 7; ≥ 5 for ages 8 – 39; ≥ 4 for 40 – 59 year olds; ≥ 3 for women 60 – 69 and ≥ 2 for those over the age of 70. In males the recommended cut-offs were: ≥ 5 in those aged 3 – 7; ≥ 4 for ages 8 – 39; ≥ 2 for 40 – 59 years and ≥ 1 for men over the age of 60.

Other clinical signs associated with hip joint laxity include increased internal and external hip rotation (> 60^{o} in either direction) and the lateral knee joint line less than three inches from the plinth surface when placing the patient's leg in the figure-of-four position (Kalisvaart and Safran, 2015).

2.12 Baecke Habitual Activity Questionnaire

Participants in this study completed a Baecke Habitual Activity Questionnaire to ensure work, sport and leisure activity were also similar across the two groups (Van Dillen, Bloom, Gombatto and Susco, 2008; Ono et al., 2007). Ono et al. (2007) studying the reliabilty of the Baecke Questionnaire in women with hip OA showed an Intraclass Correlation Coefficient (ICC) of >0.75.

Chapter 3 Methods

3.1 Study Design

This is a quantitative, cross-sectional, analytical study.

3.2 Study Setting

Pilot study participants were assessed at the University's physiotherapy department on the education campus and in the researcher's practice rooms in Rosebank Johannesburg. The main and reliability study testing was also conducted in the researcher's rooms.

3.3 Participants

3.3.1 Source of Participants

The pilot study consisted of university hockey players and age-appropriate adults from the public (see Appendix B for ethics certificate). Physiotherapy students and volunteers under the age of 40 were enlisted for the reliability study (see Appendix B for ethics, faculty and departmental certificates). .

A convenience sample of male and female adults, over the age of 40, with and without recurrent and chronic localised non-specific lumbar pain, were recruited for the main study (see Appendix B for ethics certificate). These individuals were recruited through signage in the researcher's, medical practitioner's and adjacent biokineticist's rooms; through the researcher's personal Facebook account and Facebook community and sports group posting; via community and sport's club notice boards; by electronic pamphlet dissemination to sporting association's members; using leaflets distributed at sporting events and through word of mouth. Interested parties were emailed an information sheet (see Appendix C), a screening questionnaire (see Appendix D) and an informed consent form (see Appendix E) beforehand. Once eligibility was determined, appointments were booked with successful candidates.

3.3.2 Sample Size

The original sample size calculation realised a total of 142 participants, 71 for each group. This gave a power of 90%; an alpha of 5%; based on the mean of group one (lumbar pain group) being 54.15^{o} and that of group two (non-lumbar pain group) being 61.21^{o} (Van Dillen et al., 2008). A larger sample size was envisaged to ensure outcome sensitivity.

Due to time constraints and lack of participant interest, smaller sample sizes were obtained for the main study, namely 63 participants for the lumbar pain group and 32 participants for the control group. A power calculation was determined using the asymptomatic lumbar extension pain subgroup and the lumbar extension control subgroup ROM results. The mean (standard deviation) ROM for the asymptomatic lumbar extension pain subgroup and the lumbar extension control subgroup was -11.93^{o} (±6.02^{o}) and -8.05^{o} (±4.84^{o}) respectively. The asymptomatic lumbar extension pain subgroup consisted of 28 participants and the lumbar extension control subgroup, 32. Assuming a 5% level of significance, a power of 76.3% was estimated.

3.3.3 Sample Selection

The researcher was originally hesitant about placing elderly low back pain participants in gravity dependent positions, the Thomas Test being of greatest concern. Lumbar extension caused by the ipsilateral leg falling below the edge of the plinth could potentially have a detrimental effect on individuals with spondylolisthesis, spondylolysis, anterolisthesis and stenotic conditions. Further, he was tentative about placing participants with these pathologies in a prone position and testing hip extension. Here too the spine could be pulled into an end range extended, and symptomatic position. As a result a younger sporting population that required considerable lumbar, hip and hamstring ROM was chosen. Hockey was selected, since it is a non-contact, weight-bearing sport that conformed to these criteria. A convenience sample of male and female university and club hockey players with and without recurrent or chronic, localised back pain was recruited (see Appendix B for this ethics certificate). Regrettably, in spite of considerable effort, there was minimal interest. It became apparent during the pilot study that it would be necessary to adopt a different population. A systematic review showed that low back pain is most prevalent among people from 40 to 80 years of age (Hoy et al., 2012), peaking between the ages of 41 and 50 (French et al., 2015), while hip OA develops from age 50 onwards (Altman et al., 1991). An amendment to the original ethics approval was applied and granted for the inclusion of participants age 40 upwards (see Appendix B for this ethics certificate). Additional exclusion criteria were added to identify and eliminate vulnerable volunteers. Thus, eight of the 11 pilot study participants were younger hockey players, the remainder were over the age of 40.

Since overweight and obese people have an increased risk of low back pain (Shiri et al., 2010) and because higher Body Mass Index (BMI) has been shown to reduce hip rotation ROM (Kouyoumdjian et al., 2011), overweight and obese participants were excluded from the initial proposal. However, a surprising number of hockey pilot study volunteers were over the normal 24.9 BMI limit. Three of the six were “overweight”, while two participants were on the high side of normal, at 24.4 and 24.8. Only one person was situated comfortably within range at 21.9. In order to be more realistic, the BMI ceiling was raised to ≤ 29.9 kg/m2 - overweight participants were therefore included but obese volunteers excluded.

In order to standardise the hip extension testing position and identify those who would also likely adversely react to the Thomas test position, persons unable to lie prone were excluded. People with hip conditions were similarly excluded from both groups, namely if they had groin, anterior thigh, lateral hip or buttock pain. As were those who were receiving or had received musculoskeletal treatment, within the previous six months (Shum, Crosbie and Lee, 2005), or were regularly making use of anti-inflammatories or analgesics, ≥ 2 times per week (Khalaf et al., 2018), for a hip condition.

People whose weakened tissues may not have tolerated the strong stretch necessary in the testing procedure, were likewise excluded. Specifically, those with osteoporosis (with a high risk of fracture), exposed to long-term steroid usage or currently or historically diagnosed with a systemic inflammatory condition (Bade et al., 2017; Van Dillen, Bloom, Gombatto and Susco, 2008). Pregnant women were also prevented from participation (Bade et al., 2017; Van Dillen, Bloom, Gombatto and Susco, 2008) because of its sometime, short term provocation of lumbar pain, its effects on joint elasticity and its impact on patient positioning.

As the purpose of the study was to determine an association between altered hip range and lumbar symptoms, any hip (Vad et al., 2004) and knee pathologies which could have had a strong mechanical effect on the lumbar spine were excluded. Therefore individuals with histories of hip and knee trauma and/or surgery, chronic symptomatic knee problems, congenital hip disorders and true leg length discrepancies (Simoneau et al., 1998) were also exempted. Leg length discrepancies of ≥ 20mm are thought to be significant (Gurney, 2002) and were thus excluded.

In keeping with manual physiotherapy treatment guidelines (Maitland, 1986), participants with cauda equina and cord signs (Bade et al., 2017) and symptoms were excluded. A serious neurological condition could be aggravated by taking the hip or lumbar spine through range and would also influence hip ROM. Similarly, because non-specific lower back pain was being researched and to ensure, in certain instances, greater parity across the experimental and control groups, serious spinal conditions were excluded. Namely, “serious spinal complications (e.g. tumour or infection), marked kyphosis or scoliosis, spondylolisthesis, spinal stenosis, spinal instability, spinal fracture, ankylosing spondylitis, disk herniation, lower extremity impairment such as previous lower extremity surgery… history of unresolved cancer” (Van Dillen et al., 2008) and in the same vein, anterolisthesis. Additionally, individuals who had had lumbar surgery were also omitted (Bade et al., 2017; Vad et al., 2004).

The inclusion criteria for the lumbar-pain group were individuals with recurrent, localised lumbar pain, defined as multiple episodes of pain occurring on less than half the number of days in a 12-month period or chronic localised lumbar pain, defined as symptoms on more than half the number of days in a 12-month period, occurring in a single or multiple episodes (Van Dillen et al., 2008). The motivation for selecting this population was to isolate a group of people who regularly experienced non-specific lumbar symptoms without an overt hip condition.

The control (pain-free) group consisted of individuals without recurrent or chronic lumbar pain, that is, they had not experienced pain for greater than two weeks in the past year, in order to exclude exercise induced muscle soreness (Vad et al., 2004). This group of participants without lumbar and hip problems would serve as the control. Furthermore, they were excluded if they were currently receiving or had received musculoskeletal treatment within the previous six months (Shum, Crosbie and Lee, 2005) or were regularly using anti-inflammatories or analgesics, ≥ 2 times per week (Khalaf et al., 2018), for a hip or lumbar condition.

To realise more precise measurements, participants were rescheduled if they had stretched, warmed-up or played sport on the day of testing. Participants were also urged to refrain from taking analgesics and anti-inflammatories on the day of testing to aid awareness of any lumbar symptoms.

To summarise:

Inclusion Criteria for Lumbar Pain Group
• Participants 40 years of age and older (Hoy et al., 2012). • Individuals with recurrent lower back pain or chronic lower back pain. Recurrent lower back pain was defined as symptoms present on less than half the number of days in a 12-month period, occurring in multiple episodes over the year. Chronic lower back pain was defined as symptoms present on greater than half the days in a 12-month period, occurring in a single or in multiple episodes (Van Dillen et al., 2008).
Inclusion Criteria for Control (Lumbar Pain-Free) Group
• Participants 40 years of age and older (Hoy et al., 2012). • Individuals without lower back pain. Defined by being asymptomatic for greater than two weeks in the past year (Vad et al., 2004); not having received, within the previous six months, or currently receiving physiotherapy, chiropractic, osteopathic and/or biokinetics treatment (Shum, Crosbie and Lee, 2005) and/or regularly taking anti-inflammatories or analgesics, ≥ 2 times per week (Khalaf et al., 2018), for a lumbar condition.

Exclusion Criteria for All Participants
• Participants younger than 40 years of age (Hoy et al., 2012). • Individuals who were unable to lie prone. • Volunteers with a Body Mass Index ≤ 29.9 kg/m^2. • Participants rescheduled if they had taken anti-inflammatories or analgesia 24 hours prior to testing. • Participants rescheduled if stretched, warmed-up or had played sport on the day of testing. • Individuals who had had surgical treatment to their lumbar spines, knees or hips. • Individuals with lower limb and cauda equina neurology. • Individuals with significant leg length discrepancy – greater than or equal to 20mm (Gurney, 2002) • Congenital hip problems • A diagnosis by a physician, currently or historically, of a systemic inflammatory condition. • If a physician had historically diagnosed any of the following: “serious spinal complications (e.g. tumour or infection), marked kyphosis or scoliosis, spondylolisthesis, [spondylolysis or anterolisthesis], spinal stenosis, spinal instability, spinal fracture [or pelvic, coccygeal or hip fracture], ankylosing spondylitis, [acute or sub-acute lumbar] disk herniation, lower extremity impairment such as previous lower extremity surgery”… history of unresolved cancer, osteoporosis, or current pregnancy” (Van Dillen, Bloom, Gombatto and Susco, 2008). • Prolonged steroid use (Maitland, 1986; Hengeveld and Banks, 2014). • Persons with chronic symptomatic knee problems. • Volunteers that currently had pain in the groin, lateral hip, thigh or butt. • Those that had received or were receiving physiotherapy, chiropractic, osteopathic, and/or biokinetics treatment within the past six months for a hip condition - namely, pain experienced in the groin, lateral hip, thigh or butt (Shum et al., 2005). • Persons regularly (two or more times per week) using anti-inflammatories or painkillers for a hip condition (Khalaf et al., 2018).

3.4 Instrumentation and Outcome Measures

3.4.1 IMUs

An IMU (Shemesh Health Solutions Pty Ltd, Johannesburg, South Africa) was used exclusively for hip ROM testing in this study. Previous comparisons of a wireless IMU system with an optoelectronic one, showed IMU's between-session, intra-rater ICC for hip ROM ranged from 0.6 to 0.95 (Al-Amri et al., 2018). A discussion on the concurrent validity of IMUs, robotic systems and optoelectronic motion capture systems; the rationale for the validity testing; the experimental setup; and the validity studies conducted on the device appears in Chapter 4 below.

3.4.2 Extendable Goniometer

In spite of the earnest adoption of IMU's in this study, a goniometer was still necessary to standardise the hip abduction and adduction measurement's starting point. As traditionally dictated, the femur was positioned at a 90^{o} angle to the contralateral anterior superior iliac spine (Clarkson, 2000; Nussbaumer et al., 2010). A Baseline "XTender" 360° extendable goniometer (Fabrication Enterprises Inc. White Plains, New York) was employed for these ends. Comprising of extendable stationary and moveable arms, it ensured more accurate alignment over the long length of the femur.

The validity and reliability of goniometers in hip ROM measurement have previously been confirmed (Roach et al., 2013; Clapis et al., 2008). A goniometric intra-examiner ICC of 0.8 was achieved through prone internal and ER and MTT assessment (Roach et al., 2013). While an ICC of 0.92 was attained through inter-examiner goniometric testing also making use of the MTT (Clapis et al., 2008). In contrast, Roach et al. (2013) found low goniometric inter-tester reliability (ICC <0.50). Other studies have made use of one examiner to reduce inter-tester inconsistencies (Vad et al., 2004), similarly in this research, the author performed all the passive hip movement assessments.

3.4.3 Baecke Questionnaire

On arrival, participants completed the Baecke questionnaire online. This was utilised to identify their work, sport and leisure activities and determine whether these daily pursuits were similar across the two groups (Van Dillen et al., 2008; Ono et al., 2007).

3.4.4 Height and Weight Measurements

Once they had removed their shoes and donned loose-fitting shorts, their height (Wenzhou Kindcare Import and Export Company, Wenzhou, China; Model KT-GF06A) and weight (Tanita Corporation, Tokyo, Japan; Model UM-075) were taken to ensure they fell within the prescribed BMI parameters.

3.4.5 Beighton Scale

Participants were then assessed with the Beighton scale test to discern joint hypermobility differences across the two groups. This method assesses whether excessive passive joint range exists at nine sites across the body. A point is scored if the following positions are achieved (The Ehlers-Danlos Society, 2019; Kalisvaart and Safran, 2015):

- In 90° elbow flexion, forearm pronation, wrist neutral and hand flat on a surface, the fifth finger is able to extend greater than 90° at the metacarpophalangeal joint. This is assessed and scored bilaterally (Fig. 3.1A).
- In 90° shoulder flexion, elbow extension, forearm pronation and wrist flexion, the thumb is abducted and touches the ipsilateral forearm. This is assessed and scored bilaterally (Fig. 3.1B).
- In approximately 90° shoulder abduction and full ER and forearm supination, the elbow is able to hyperextend greater than 10°. This is assessed and scored bilaterally (Fig. 3.2).
- In standing, with feet shoulder-width apart and knees locked in genu recurvatum, knee hyperextension achieves an angle of greater than 10°. This is assessed and scored bilaterally (Fig 3.3A).
- In standing, with knees straight and feet shoulder-width apart, the participant is able to bend forward and place both hands flat on the floor just forward of their feet (Fig. 3.3B).

A score of ≥ 5 out of 9 is defining (Juul-Kristensen et al., 2017). Each participant's results were recorded.

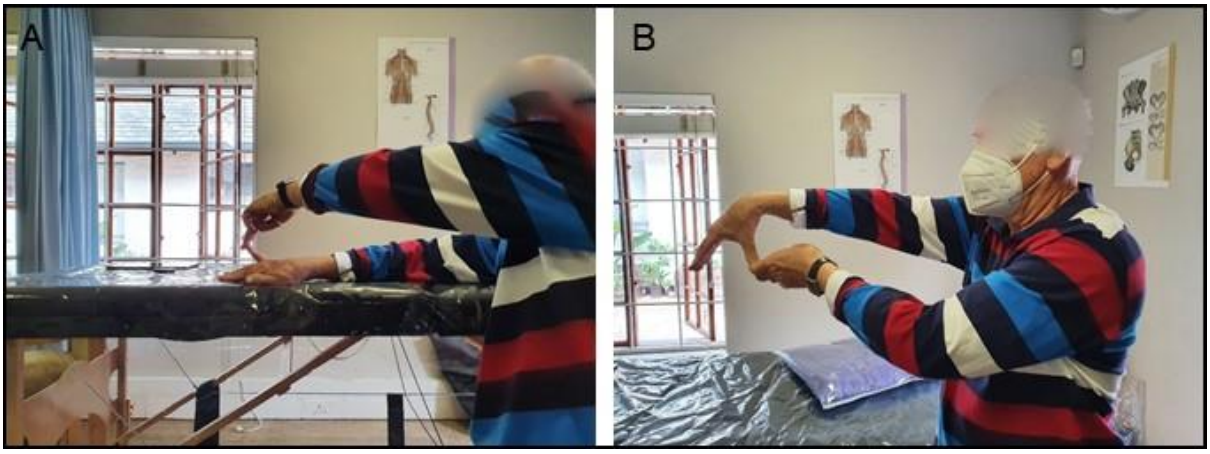

Fig. 3. 1 A) Beighton scale testing of the fifth finger. The finger is pulled into maximal extension. B) Thumb being pulled toward the forearm for Beighton flexibility testing.

Fig. 3. 2 Positioning for testing of Beighton scale elbow extension. Participant attempts to maximally extend his elbow.

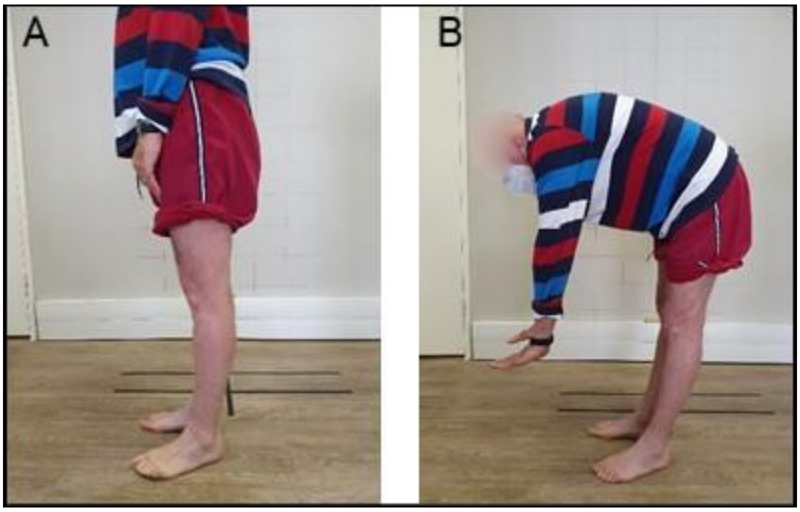

Fig. 3. 3 A) Beighton scale knee extension testing. The knees are actively extended into maximal extension. B) Participant bends forward attempting to place his palms flat on the floor.

3.4.6 Pre-testing Preparation and Testing Approach

The sequence of passive hip joint ranges measured was block randomised by drawing lots. The blocks were the three rotation positions; extension; abduction/adduction and hip flexion, SLR and Thomas Test positions. Side and order of rotation position testing were also randomised. This was done to reduce the effects of increasing flexibility realised through the assessment process.

Testing took place on a wooden plinth. Limbs were cantilevered over a wooden wedge and supported with a wooden stool and chair when necessary. This was used to negate any inaccuracies created by metal furniture's ferromagnetic effects on the sensor's magnetometer (Luinge and Veltink, 2005). Similarly, heaters and air conditioners were switched off to reduce any electromagnetic fields.

The following bony landmarks were identified and marked with ink on the participant's left and right sides: the medial, lateral, inferior, superior borders and the resulting midpoint of the patella (Clarkson, 2000; Nussbaumer et al., 2010); a point, one length of the sensor (4.5 cm), proximal to the midpoint of the patella; a marked axis, extending from the tibial tuberosity to the bisected midpoint between the malleoli (Kouyoumdjian et al., 2011); a point, on the delineated shin axis, approximately 10 cm proximal to the most inferior point of the lateral malleolus (Malliaras et al., 2009; Van Dillen et al., 2008); and the left and right ASIS (see Fig. 3.4 and Fig. 3.5 below; these images are available in a higher resolution for the reader's perusal at www.dropbox.com (email/account: kermann@tiscali.co.za ; password: research123). The patella midpoint was confirmed with a tape measure; the midpoint between the malleoli was identified using a sliding caliper (Cescorf, Porto Alegre, Brazil); and the axis linking the tibial tuberosity and bi-malleolar midpoint was marked using a flexible metal ruler (Foska, China). The IMU's placement and positioning was governed by these landmarks and the findings of the validation studies (see Chapter 4). The sensor was held in position on these predetermined points with elastic strapping. The participants wore non-restricting clothing which was kept free of the sensor. After connecting the sensor through Bluetooth to an Ipad (Apple Incorporated, Cupertino, California), readings were taken from the application's spirit level and "Free Movement's Rotation" angle measurement setting. Only one sensor was used at any given time, to avoid confusion identifying the relevant reading.

Fig. 3. 4 Applied inking demarcating the borders and centre of the patella; a point 4.5 cm above the patella centre; tibial tuberosity; bisected bimalleolar point; the axis running from the tibial tuberosity to the bisected bimalleolar point and point 10cm above the tip of the lateral malleolus.

Fig. 3. 5 Inking of the left and right ASIS.

Passive joint range testing was used in the study to negate inaccuracies caused by muscle weakness. Movement was to the end of range and/or to the onset of lumbar pain. Passive joint end range was denoted with the examiner feeling the joint range limit, palpation of pelvic compensation (Van Dillen et al., 2008; Ellison et al., 1990), and/or the participant communicating a strong, tolerable, pain-free stretch (Moreno-Perez et al., 2016). The researcher performing the passive hip range testing was blinded (Beneck et al., 2018; Ellison et al., 1990) to the measurements, ensuring that he was not biased in achieving a certain outcome. The only exception to blinding was during Thomas Test testing, where gravity and muscle flexibility determined the end point. The participant, in sight of the IMU's measurements on the tablet, memorised and disclosed the results for capturing at the end of each specific ranges' testing. Participants were encouraged to communicate any memory lapses. In the event this occurred, another trial was performed. Each joint range was measured three times and an average was calculated (Van Dillen et al., 2008; Beneck et al., 2018). On the odd occasion, when a fault was suspected, a fourth trial was performed. This was carried out to ensure accurate performance of the technique and to eliminate any error. The researcher was once again blinded to the fourth trial's result. The most aligned of the three trial's measurements were then captured (Uding et al., 2019).

The hip ranges assessed, participant's position, IMU position, application's setting and passive movement procedure is outlined in detail below:

3.4.7 MTT Testing Procedure

With the participant supine, having performed a bridge to position the pelvis in neutral, the IMU was placed on the mid, lateral thigh (Roach et al., 2013; Roach, et al., 2015). The sensor's spirit level was used to determine when it was perfectly horizontal and then it was taped to the thigh in this position. The IMU was "upright" with the casing's ridges against the participant's skin. The sensor's spirit level functionality was used to measure this range. As the application did not display negative values, the researcher kept sight of the spirit-level icon and added a negative sign to the result if it showed that the thigh had dropped below the horizontal. The IMU did not require recalibration for each trial.

The participant was then moved down the bed, so that their ischia perched on the edge of the table and legs protruded over the bottom of the plinth. The pelvis was not secured with belting. Participants were assisted in simultaneously moving both flexed knees toward their chests. The researcher palpated the lumbar lordosis as he passively flexed and extended their hips. Both thighs were held in position when the lordosis was felt to flatten against the plinth surface (Sahrmann, 2002; Clapis et al., 2008; Klassbo et al., 2003; Beneck et al., 2018). The participant was then instructed to hold one knee in the attained flexed position as the contralateral thigh was passively lowered down into extension. Gravity and the passive tissue stretch determined the end range point, the knee was allowed to move freely. The test hip was kept in neutral abduction (Fig. 3.6A). This was performed three times and the test thigh's angle with respect to the horizontal was recorded.

In order to determine the effects of the one-joint hip flexors on the hip ROM while negating those of rectus femoris and tensor fascia lata (Peterson Kendall et al., 1993; Van Dillen et al., 2000), the whole procedure was repeated, but on the second occasion the knee was passively extended after the thigh was lowered to its end position. Again the hip was maintained in neutral abduction (Fig. 3.6B). This test was also performed three times on each side. The test thigh's angle with respect to the horizontal, was similarly recorded. These values, when greater than zero, were later added to the contralateral SLR (SLR) range measurement in keeping with Peterson Kendall et al.'s (1993) guidelines. Please refer to section 2.7.3 above for this rationale.

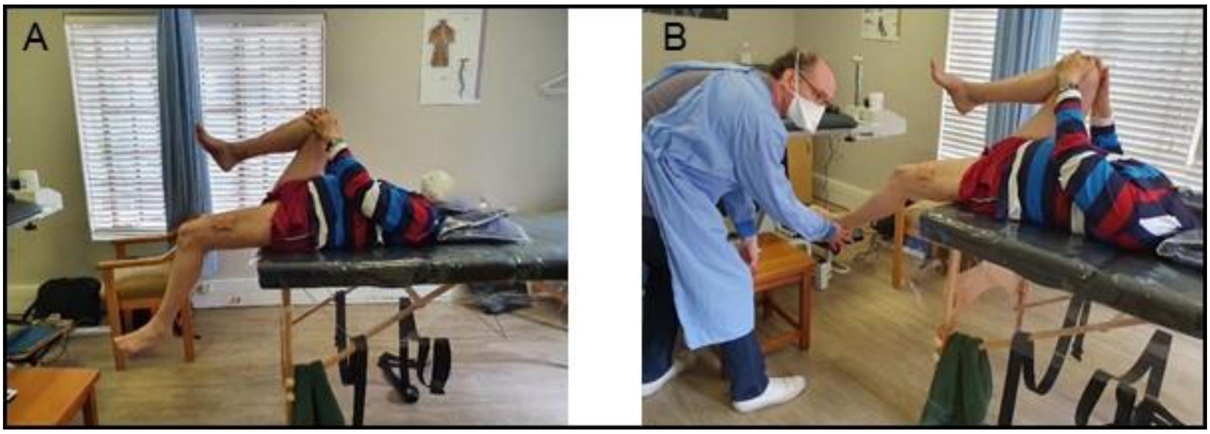

Fig. 3. 6 A) MTT end position with gravity assisted knee flexion. B) MTT end position with passive knee extension.

3.4.8 Straight-Leg Raise (SLR) Testing Procedure

The participant was positioned in supine, neutral hip rotation and abduction/adduction with the knee extended and the ankle relaxed in plantarflexion. The lumbar spine and sacrum were flat against the plinth. The head was neutral on one pillow and the ankle in neutral inversion/eversion to contain neural tension (Gugliotti et al., 2018). The participant performed a bridge to achieve neutral pelvis. A belt was secured across the contralateral thigh. Restraining the contralateral limb prevented excessive compensatory posterior pelvic tilt once the ipsilateral limb reached end of range (Peterson Kendall, Kendall McCreary and Geise Provance, 1993).

Again, the IMU was placed midway on the lateral thigh (Gugliotti et al., 2018; Clarkson, 2000). The sensor's spirit level was used to determine when it was perfectly horizontal and then it was taped to the thigh in this position. The IMU was "upright" with the casing's ridges against the participant's skin. Having demarcated the 0^{o} starting position with the IMU's spirit-level, the SLR range was measured with the device's angle measurement function. Following the validation studies (see Chapter 4), the IMU did not require recalibration for each movement.

The leg was raised with knee held in extension and flexion taking place at the hip. End range marked by the researcher noting a tightening of the hamstring musculature (Fig. 3.7).

Fig. 3. 7 End range passive SLR with the contralateral leg securely belted.

3.4.9 Hip Flexion Testing Procedure

The participant was positioned in supine. Having performed a bridge, achieving a neutral pelvis with lumbar spine and sacrum now relaxed flat against the plinth surface, the hip was placed in neutral rotation and abduction/adduction (Beneck et al, 2018) with knee extended. No belting was required to fix the pelvis.

The IMU was placed on the lateral thigh (Nussbaumer et al., 2010), midway between the greater trochanter and lateral femoral epicondyle (Nussbaumer et al., 2010; Clarkson, 2000; Beneck et al, 2018). The sensor's spirit level was used to determine when it was perfectly horizontal and then taped to the thigh in this position. The IMU was “upright” with the casing’s ridges against the participant’s skin. The application was then calibrated and the range measured with the device’s angle measurement function. The sensor did not require recalibration after each measurement.

The researcher’s hand was placed under the lumbar lordosis and the hip flexed till bony end-feel was obtained or the lumbar spine was felt to flatten (Fig. 3.8) against the plinth surface (Beneck et al, 2018).

Fig. 3. 8 End range hip flexion with IMU in situ on the lateral thigh.

3.4.10 Hip Extension Testing Procedure

The participant was positioned prone without a pillow under the pelvis. The patient’s hips were in neutral abduction/adduction and rotation, knee extended, with feet over the bottom of the plinth (Clarkson, 2000). No belting was used across the pelvic crest.

The sensor was repositioned so that it was “upright” once again with the casing’s ridges against the participant’s skin. The IMU was placed on the lateral thigh, between the greater trochanter and lateral femoral epicondyle (Roach, San Juan, Suprak, and Lyda, 2013; Roach et al., 2015). The sensor’s spirit level was used to determine when it was perfectly horizontal and then it was taped to the thigh in this position. The application was calibrated and the range measured with the device’s angle measurement function. As per the validation study findings the sensor did not require recalibration after each measurement (see Chapter 4).

While the pelvis was stabilised with the researcher’s proximal hand or forearm, the hip was extended by his distal hand, placed under the anterior surface of the participant’s knee (Fig. 3.9) (Clarkson, 2000).

Fig. 3. 9 Passive hip extension performed while the pelvis is stabilised.

3.4.11 Hip Abduction Testing Procedure

The participant was positioned supine, pelvis level, having performed a bridge to achieve neutral pelvis. The left and right ASIS, the medial, lateral, inferior, superior borders and the resulting midpoint of the patella were identified and marked with ink. The starting position, hip adduction/adduction neutral, was determined by a Baseline “XTender” 360° extendable goniometer (Fabrication Enterprises Inc. White Plains, New York). Its axis was placed on the ipsilateral ASIS, the movable arm pointing toward the marked ipsilateral patella midpoint and the stationary arm to the contralateral ASIS, 90º apart (Fig. 3.10) (Clarkson, 2000; Nussbaumer et al., 2010). Belting could not be used to restrain the pelvis, as it obstructed placement of the goniometer.

Fig. 3. 10 Aligning the goniometer axis on the ipsilateral ASIS.

The sensor's lower margin was secured one length of the sensor (4.5 cm) proximal to the midpoint of the patella. The "upright" side of the sensor was proximal, that is, closer to the hip with the casing's ridges against the participant's skin. This range was evaluated using the IMU's angle measurement functionality. As gyroscope drift was identified in this plane during the validation studies (see Chapter 4), it was recalibrated to zero, referenced by the goniometer, with each trial.

Passive abduction was executed with the researcher standing on the ipsilateral side of the plinth. The pelvis was manually stabilised with his forearm across both ASIS's and the other hand around the ipsilateral ankle (Fig. 3.11). The test hip was moved into abduction three times on each side.

Fig. 3. 11 Passive end range abduction with sensor secured on the anterior thigh.

3.4.12 Hip Adduction Testing Procedure

Here, the participant was positioned in supine and the pelvis levelled in the same fashion as for abduction testing above. The test side was also placed in its neutral starting position, using the same methodology, ink markings and extendable goniometer, as outlined in the abduction testing procedure above. The pelvis was not belt controlled as this would have obscured the goniometer's placement.

The IMU placement and application settings were also identical, again the sensor was recalibrated at the start of each trial.

The researcher, standing on the contralateral side of the plinth, manually restrained both ASIS's with his forearm and placed the contralateral leg in some abduction to allow freedom of movement for the test limb (Clarkson, 2000; Nussbaumer et al., 2010). Maintaining pelvic stabilisation with his forearm and gripping the ipsilateral ankle, the test hip was moved into adduction three times on each side (Fig. 3.12).

Fig. 3. 12 End range adduction with the contralateral limb in some abduction.

3.4.13 Hip Rotation (In Prone) Testing Procedure

Once the participant was positioned in prone and aligned square on the plinth, with the hip in neutral abduction/adduction, the pelvis was belt restrained. A pillow was not placed under the lumbar lordosis. A plastic try-square brace was Velcro strapped onto the calf and thigh to maintain the knee in 90^{o}. If the contralateral leg impeded ER, it was placed in some abduction (Roach et al., 2013; Clarkson, 2000; Van Dillen et al., 2008; Ellison et al., 1990).

The IMU's midpoints were lined up on a marked axis, extending from the tibial tuberosity to the bisected mid-point between the malleoli (Kouyoumdjian et al., 2011). It was strapped anteriorly to the shin (Clarkson, 2000), approximately 10 cm proximal to the most inferior point of the lateral malleolus (Malliaras et al., 2009; Van Dillen et al., 2008). The sensor's "upright" side was distal, that is closer to the foot, with the casing's ridges against the participant's skin.

With each and every reading, the shin was moved to the vertical 0^{o} starting position guided by the IMU's spirit-level function. The angle measurement function was then activated and used to measure the hip rotation ranges. In order to accurately compare the rotation range, the same procedure was repeated in all three sagittal-plane-positions.

The researcher stabilised the pelvis with one hand and held the participant's ankle in the other as he moved the hip through to end range internal (Fig. 3.13A) and ER (Fig. 3.13B). The test was performed three times to each side.

Fig. 3. 13 A) Hip IR with the contralateral hip in neutral abduction/adduction. B) Hip ER with the contralateral hip in sufficient abduction to allow unobstructed movement of the ipsilateral limb.

3.4.14 Hip Rotation (In Sitting) Testing Procedure

The participant was placed in sitting, legs over edge of the plinth, with the knee flexed 90^o and the hip in neutral abduction/adduction. A folded towel was placed under the distal thigh to ensure 90^o angles at the hip and knee (Clarkson, 2013). A belt was secured across the lap to restrain any pelvic movement. The contralateral foot was placed on a stool and the participant, sitting upright, held onto the lip of the plinth (Clarkson, 2013). Once again, if the contralateral leg impeded ER, it was placed in some abduction (Roach et al., 2013; Clarkson, 2000; Van Dillen et al., 2008; Ellison et al., 1990).

The IMU was strapped anteriorly onto the shin (Clarkson, 2000), its midpoints were aligned on an axis extending from the tibial tuberosity to the bisected mid-point between the malleoli (Kouyoumdjian et al., 2011), approximately 10 cm proximal to the most inferior point of the lateral malleolus (Malliaras et al. 2009; Van Dillen et al., 2008). The sensor's "upright" side was proximal, that is closer to the tibial tuberosity, with the casing's ridges against the participant's skin.

Each time the shin was moved to the vertical, 0^{o} starting position guided by the IMU's spirit-level function. The angle measurement function was then activated and used to measure the hip rotation ranges.

The researcher moved the participant's ankle through the range and stabilised the knee with the other hand, preventing pelvic tilt at the end of range. IR (Fig. 3.14A) and ER (Fig. 3.14B) was measured three times on each side.

Fig. 3. 14 A) IR in sitting with IMU sited anteriorly on the shin. B) ER in sitting with the contralateral limb in abduction and supported on a stool.

3.4.15 Hip Rotation (In Supine, Knee Over the 30º Wedge) Testing Procedure

The participant was positioned supine at the bottom of the plinth. The thigh, resting on a wooden, padded wedge (PlayOn, Johannesburg, South Africa), was positioned in 30º of flexion, neutral abduction/adduction and the pelvis was then belt restrained. The test side ankle was clear of the plinth's edge with knee at 90º over the wedge, the contralateral leg supported at the ankle over the back of a wood chair. In the event that the contralateral leg impeded ER, it was placed in some abduction (Fig. 3.15A) (Roach et al., 2013; Clarkson, 2000; Van Dillen et al., 2008; Ellison et al., 1990).

The same line drawn down the anterior of the participant's shin, extending from the tibial tuberosity to the calliper-determined bisected mid-point between the malleoli (Kouyoumdjian et al., 2011; Young et al., 2014) provided the axis for mounting the IMU. The IMU's midpoints were aligned on this axis, strapped onto the shin (Clarkson, 2000) approximately 10 cm proximal to the most inferior point of the lateral malleolus (Malliaras et al., 2009; Van Dillen et al., 2008). The sensor's "upright" side was proximal, that is, closer to the tibial tuberosity, with the casing's ridges against the participant's skin.

Once the participant was in position, the IMU's spirit-level was activated and the limb moved to the "vertical", where the application exhibited "0º". Rotation range was measured from this starting reference point (Kouyoumdjian et al., 2011; Clarkson, 2013). The angle measurement utility was then used to find the internal and ER range. This procedure was repeated with each trial.

During the testing, the researcher moved the participant's ankle through the range and stabilised the knee with the other hand to reduce pelvic tilt at end range. IR (Fig. 3.15B) and ER (Fig. 3.15C) was measured three times on each side.

Fig. 3. 15 A) Participant positioned supine with hip in 30º flexion. B) IR testing. C) ER testing over 30º wedge with contralateral leg in abduction and supported over the back of a wooden chair.

3.4.16 Physiological Lumbar Movement Testing Procedure

Every participant's active lumbar ROM was then assessed. Standing, with legs shoulder-width apart, active lumbar flexion (Fig. 3.16A), extension (Fig. 3.16B), left (Fig. 3.16C) and right lateral flexion, left (Fig. 3.17A) and right rotation and deep squatting (Fig. 3.17B), allowing heels to lift off the floor, were tested. Participants moved to the onset of lumbar pain or to the end of range. The only result noted, was whether or not each movement elicited any lumbar pain.

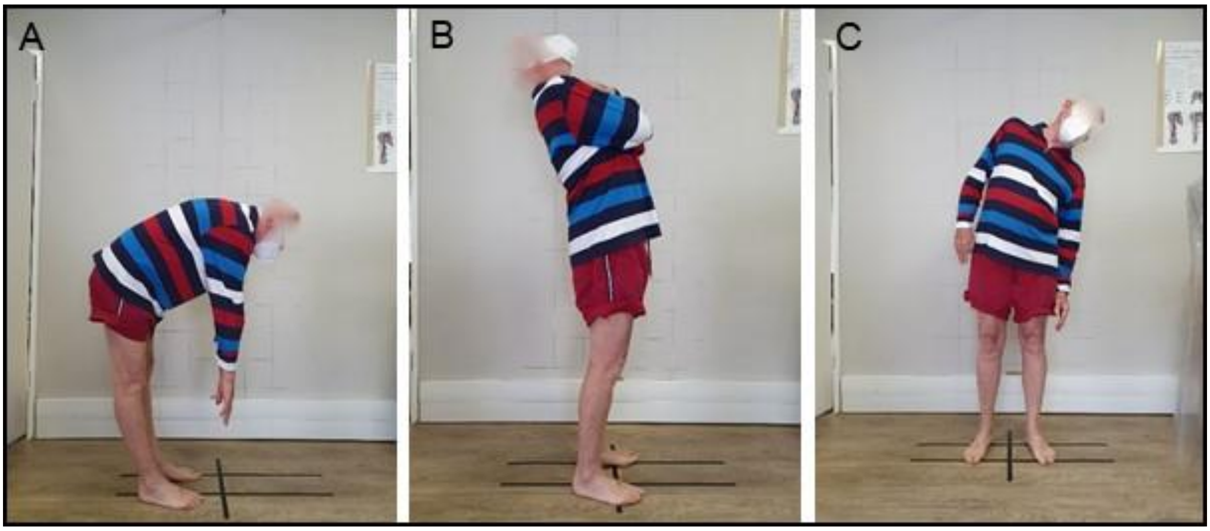

Fig. 3. 16 A) Lumbar flexion. B) Lumbar extension. C) Lumbar left lateral flexion.

Fig. 3. 17 A) Lumbar left rotation. B) Squatting.

3.5 Procedure

3.5.1 Pilot and Reliability Studies

Eleven participants were used in the pilot testing to hone the study methodology. Problems were uncovered with IMU placement and determining hip sagittal plane neutral during the pilot study. These were addressed to the best of the researcher's ability. This is outlined in greater detail in the limitations section (see section 7.4.1.5 and section 7.4.1.6) of the dissertation.

During this process it also became evident that using an assistant was not pragmatic. She was unreliable and coordinating the researcher's, assistant's and participant's schedules proved challenging. The researcher eventually assumed all responsibilities. To ensure the researcher remained blinded, participants were taught to calibrate the IMU and were only asked to memorise three values at a time. Although these duties had not been outlined in the informed consent procedure, they did not prove to be a challenge. Recalibration was a simple, repeated procedure and the participants were coached on the Ipad's functionality till they were comfortable with the process. Once a range was measured, these values were captured by the researcher. The participants' integrity were never in question. Since they had not received any information on hip ROM's normal values and because they were to obtain a report and exercises at the conclusion of the testing based on the findings, they were incentivised to report accurate answers. Belting was used to restrain the pelvis in each rotation position and the contralateral leg during SLR assessment.

Another potential problem negated during pilot testing was the identification of the starting point during rotation testing. The spirit-level function was used to identify vertical (Kouyoumdjian et al., 2011; Roach et al., 2013; Young et al., 2014) and then the angle measurement function was activated to measure the range, having proven (see Chapter 4) to be more accurate in the three hip flexion positions. Because of these teething problems, results from the pilot study were not used in the main study.

Once pilot testing was completed, reliability studies were conducted concurrently with the main study. When ethics, faculty and departmental approval was obtained, physiotherapy and occupational therapy students were recruited for the reliability testing (see Appendix B for these ethics, faculty and departmental certificates). Volunteers who did not qualify for the main study, for example individuals younger than 40, were also enrolled into the reliability study. The reliability study replicated procedures used in the main study. Test and re-test measurements of the reliability participants were conducted one to two days apart to reduce any tester bias (Beneck et. 2018). As with the pilot and main study, the researcher performing the passive testing was blinded to the measurement results (Benec, et al., 2018; Ellison, Rose and Sahrmann, 1990).

The first reliability study exposed potential problems with manual pelvic stabilisation and knee movement during rotation testing. All subsequent testing employed attentive manual stabilisation of the participant's knee in the supine 30^{o} and sitting rotation positions and of the pelvis during prone rotation assessments. A second problem, namely knee flexion and extension movement's effects on the prone rotation results was also uncovered. Further experimentation proved that knee movement of approximately 30^{o} (the exact angle was not measured) affected the IMU's measurements. A plastic try-square brace was fabricated and strapped across successive participant's knees to prevent any movement during this test. To the author's knowledge, bracing and controlling knee movement was unique to this research (Kouyoumdjian, et al., 2011; Roach, et al., 2013; Mellin, 1990; Malliaras, et al., 2009; Van Dillen, et al., 2008; Simoneau, et al., 1998; Vad, et al., 2004; Nagai, et al., 2015; Young, et al., 2014; Aefsky, et al., 2016; Murray, et al., 2009). Reliability testing was not repeated on the initial participant but subsequent reliability study measurements were more consistent demonstrating the brace's effectiveness.

3.5.2 Main Study

On arrival, a volunteer completed the Baecke Questionnaire. Their height, weight and Beighton Scale were then assessed and recorded. Next skeletal landmarks were identified and marked for IMU placement. The following hip ranges were block randomised (by drawing lots) and measured: hip flexion, SLR and MTT positions; extension; abduction/adduction; and the three rotation positions. Lumbar flexion, extension, left and right lateral flexion, left and right rotation and squatting were assessed and noted whether they were symptomatic. On conclusion of the testing, the participant's hip range results were collated with an Excel macro and discussed with them. This also usually included a short subjective examination and a quick postural assessment. Based on these findings, the volunteer was prescribed hip and/or lumbar exercises. When appropriate, a reassessment of the symptomatic lumbar movement was performed to determine the exercises' effects.

Two participants had BMI's >29.9 and were thus found ineligible for inclusion. One participant disclosed he had a history of coccygeal fracture during the procedure and his results were omitted from the study. Four of the control group participants experienced isolated lumbar symptoms on testing at the end of the assessment. On re-evaluation of their pre-assessment, screening questionnaires, two did not state any problems. The third, did report a scoliosis, but as it was not "marked" he was included in the study – he had never received treatment for the condition and inspite thereof was continuing to play field hockey at the age of 68. The fourth, had a minor knee problem which was only symptomatic after playing squash - no lumbar problems were reported. Main study testing commenced on the 23rd of December 2020 and was completed on the 30th of May 2022.

3.6 Ethical Considerations

An information sheet, participant questionnaire and informed consent form were emailed to volunteers beforehand to avoid unnecessary travel. Participants were notified that participation was voluntary and that they could withdraw from the study at any time, without any reason. In this event, any information collected was destroyed. They were also informed that the study had been approved by the Human Research Ethics Committee (Medical) of the University of the Witwatersrand and that if they had any concerns over how the study was being conducted, they could contact the chairperson of this committee. The study received ethics clearance, protocol number M181041, the reader is referred to Appendix B for the ethics clearance certificate.

Written permission was received from the Human Research Ethics Committee (Medical), Wits Deputy Registrar and Heads of the Physiotherapy and Occupational Therapy Departments to contact and invite therapy students to participate in the reliability study. Permission was also obtained from the Wits Hockey Sports Officer to contact and invite hockey players to participate in the pilot study. Where necessary, permission was acquired from sporting clubs and organisations' committees and Facebook group administrators to distribute electronic pamphlets and leaflets to their members.

All collected personal information was treated in the strictest confidence and securely stored through password protection. Only the principle researcher had access to full names and contact details. On completion of the questionnaire, participants were assigned a case number to ensure anonymity and confidentiality of their medical histories. Information collected was used for the purposes of this study only and not disseminated any further.

The hip range and lumbar movement testing was conducted in a private room. As the research took place during the Covid-19 pandemic, the following Covid-19 procedures were strictly adhered to: the room was well ventilated by external windows; bed surfaces, plastic pillow cases and equipment was sterilised before each use; an FFP2 mask was worn by the researcher; participants donned surgical or non-medical masks; to prevent contact the researcher was covered by a surgical gown which was laundered after each use and the researcher and participant sterilised their hands on meeting. The researcher was vaccinated early during the main study.

3.7 Data Management

An online Baecke Questionnaire was created on Google Forms, which saved the participant's answers to a linked Google sheet. This data was then transferred to a purposefully developed, tested and verified Excel macro, which automated each Baecke index's calculations. These results were copied to a master excel spreadsheet.

Similarly, each measured hip joint range's three trials was processed by an Excel macro. This automatically extracted the measurements from the participant assessment forms, averaged each range's trial's results and populated a spreadsheet. These average ranges were also copied to the master excel spreadsheet. The lumbar spine's symptomatic and asymptomatic movements were manually inserted into the master excel spreadsheet. A similar procedure was employed for the reliability studies' results, although only its hip ranges were processed and its SLR results were not (MTT) adjusted.

Any positive MTT with-knee-extended values were added to the contralateral SLR results and amended in the master Excel spreadsheet. These adjusted SLR values were used in all subsequent statistical analyses. Eleven participants' results needed to be modified, seven were in the pain group and the remainder control group participants. Adjustments of 0.67^o – 6.67^o to the left SLR (n = 7) and 0.33^o – 7.33^o were made to the right SLR (n = 10). Six people had bilateral iliopsoas tightness, in the remainder it presented unilaterally on the left or right.

The data was then transferred to SPSS. Thereafter, to identify any data entry errors, an analyses of the data's frequencies was performed. This was achieved by checking each variable for missing data and scrutinising their minimum and maximum values.

3.8 Statistical Analyses

Statistical analyses was conducted using IBM SPSS Statistics Version 28 (IBM, Armonk, New York). Microsoft Excel 2013 (Microsoft, Redmond, Washington) was also utilised to filter and sort the data in objectives 4 and 5. Significance was set at $p < 0.05$ for all comparisons.

A Chi-squared test of independence was performed to determine whether there was an association between gender and lower back pain. As a non-significant difference was found between both group's hip ROM variables, the complete cohort (n=95) was employed for the analysis. The hip variable's ROM values were compiled using the means and medians calculated from the pain and control group's left and right sides. The SLR results were MTT adjusted.

Analyses was performed on the cohort, split into pain (those with chronic non-specific lower back pain) and control (those without chronic non-specific lower back pain) groups. Each group's age, BMI, Beighton scores, Baecke indices and side hip ROM's means, standard deviations, ranges, medians and interquartile ranges were tabulated. Analysis was performed on the MTT adjusted, SLR results throughout. Shapiro-Wilk analyses was performed on all of the variables to determine each data set's distribution. The variables with skewed distributions, namely with Shapiro-Wilk values <0.05, were flagged. The control group's left hip extension's skewness and kurtosis (with Shapiro-Wilk score of 0.057) were also evaluated to ensure its normality.

3.8.1 Statistical Analyses Employed in Objectives 1 and 2 Determination and Comparison of the Pain and Control Group's Hip Ranges' ROM

For the studies' objective's 1 and 2, a two-tailed independent t-test was utilised to compare the group's hip range variables' means (namely, those with a normal distribution). For a two-tail alpha of 0.05, a critical value of 1.990 was selected from the students' t distribution table, as 80 was the smaller df in relation to the study calculated df of 93. The Mann Whitney U test was applied to compare the medians, when either one or both variables had a skewed distribution. Cohen's d is quoted for the normally distributed variable's effect sizes. Values of 0.20 indicating a small effect, 0.50 a medium effect and 0.80 a large effect (Bhandari, 2022). The effect sizes of the skewed data was calculated using the formula: $r = Z/\sqrt{N}$ (Latif, 2022) making use of data derived from the Mann Whitney U test analysis.

3.8.2 Statistical Analyses Employed in Objective 3 Comparison of the Pain and Control Group's Side-to-Side Hip Ranges' ROM

For the studies' third objective, comparing the lumbar pain and control group's side-to-side hip range differences, a paired samples t-test was utilised to analyse the variables with normally distributed data. The Wilcoxon Signed Rank test was used to compare the medians of the pain and control groups' side differences when either one or both variables had a skewed distribution. Analysis was performed on the adjusted, SLR measurements. Since the data was split into the same groups and same variables compared, the earlier distribution analysis was employed once again. In the pain group, for a two-tail alpha of 0.05, a critical value of 2.000 was selected from the students' t distribution table, as 60 was the smaller df in relation to the study calculated df of 62. Similarly, in the control group, for a two-tail alpha of 0.05, a critical value of 2.042 was selected from the students' t distribution table, as 30 was the smaller df in relation to the study calculated df of 31. Once more, Cohen's d was utilised for effect size on the normal variables. Effect sizes of the skewed data was calculated using the formula: $r = Z/\sqrt{N}$ (Kajka, 2021), applying data derived from the Wilcoxon Signed Rank test analysis.

3.8.3 Statistical Analyses Employed in Objectives 4 and 5 To Determine Whether There is an Association Between Hypomobile and Hypermobile Hip Ranges and their Coupled Symptomatic Lumbar Ranges

In order to determine whether an association between symptomatic lumbar ranges and hypomobile or hypermobile hip ROM exists, each specific lumbar range's coupled hip ROM's means and medians (depending on normality) were compared for significance across three subgroups. Making use of the same control group (control subgroup), the pain group was further subdivided into those participants who experienced lumbar pain during a specified lumbar range (symptomatic pain subgroup) and those who did not (asymptomatic pain subgroup). The three subgroup's coupled hip ranges were compared for significance using a one way ANOVA or Kruskal-Wallis test depending on normality.

The hip ROM data sorting and collating varied depending on the lumbar range and its coupled hip range's movement characteristics. With lumbar ranges limited by the simultaneous movement of both hips, each subgroup's participant's left and right hip range's average was calculated and collated and then their means were compared. For example, lumbar flexion's coupled hip range is left and right SLR. Since lumbar flexion range is not checked by a single hamstring's length (but a left and right SLR length asymmetry likely causes a lumbar spine torsion), the average SLR range was calculated from the left and right SLR angle measurements. Each subgroup's participant's average SLR values were then collated and their means were compared (see Fig. 3.18 below). The reader should note that the flowcharts state singular hip ranges, this was done to reduce clutter and aid understanding. These singular ranges were collated to create means and medians for analyses. This same procedure was used in the lumbar flexion-hip flexion/squat coupling; lumbar extension-hip extension coupling; lumbar extension-MTT coupling; lumbar left rotation-left hip IR(IR)/right hip ER(ER) coupling (left hip IR ROM = right hip ER ROM) and lumbar right rotation-right hip IR/left hip ER coupling (right hip IR ROM = left hip ER ROM) coupling analyses. The lumbar rotation-hip rotation coupling is explained in greater detail below.

When a single hip's range was the potential coaxial (lumbar range) limiting factor, that single range was compared across the three subgroups. For example, when performing left lumbar lateral flexion, both left hip abduction and right hip adduction ranges are active but right hip adduction's range (having the smaller anatomical range of the two) would singly affect this specific lumbar movement. Thus in this circumstance, the subgroup's right hip adduction range's mean was compared for significance (see Fig. 3.19 below). This same procedure was also used in lumbar right lateral flexion-left hip adduction coupling; lumbar left rotation-left hip IR coupling (left hip IR ROM < right hip ER ROM) and lumbar right rotation-right hip IR coupling (right hip IR ROM < left hip ER ROM) analyses.

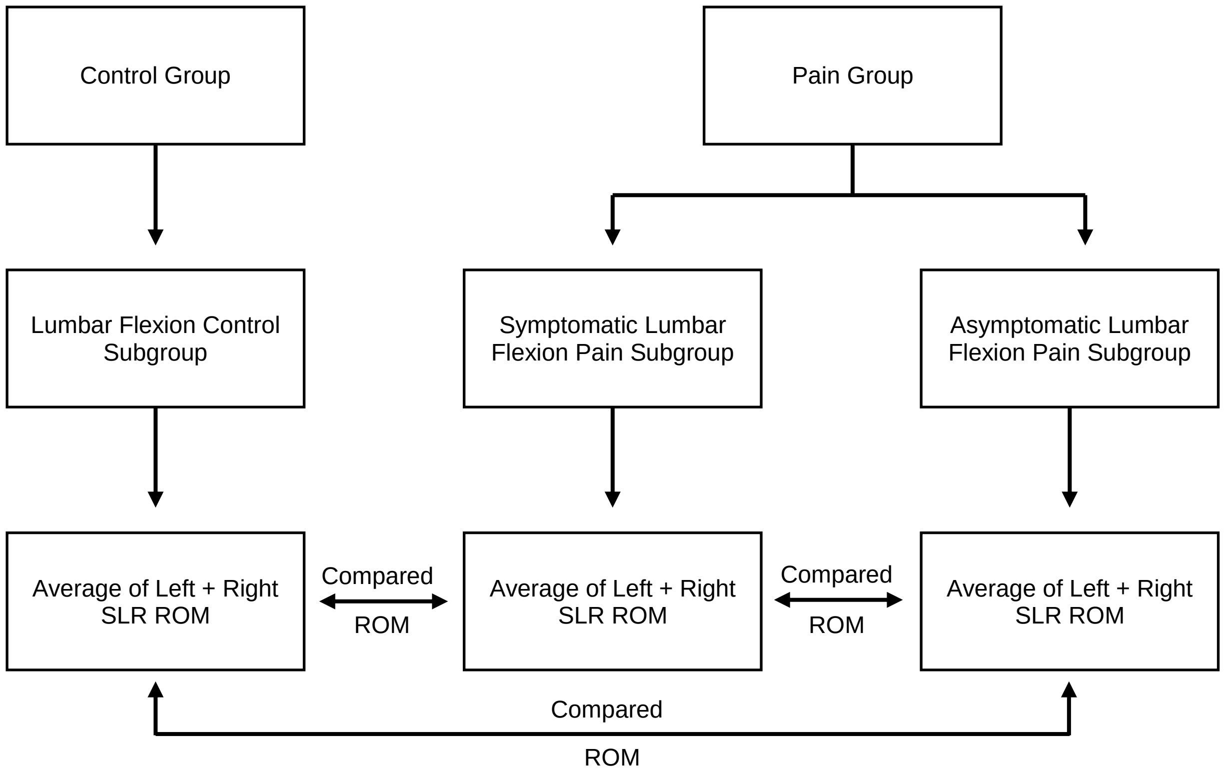

Fig. 3. 18 Schema illustrating the group splitting and hip SLR ROM sorting for the lumbar flexion–SLR coupling's pairwise comparisons.

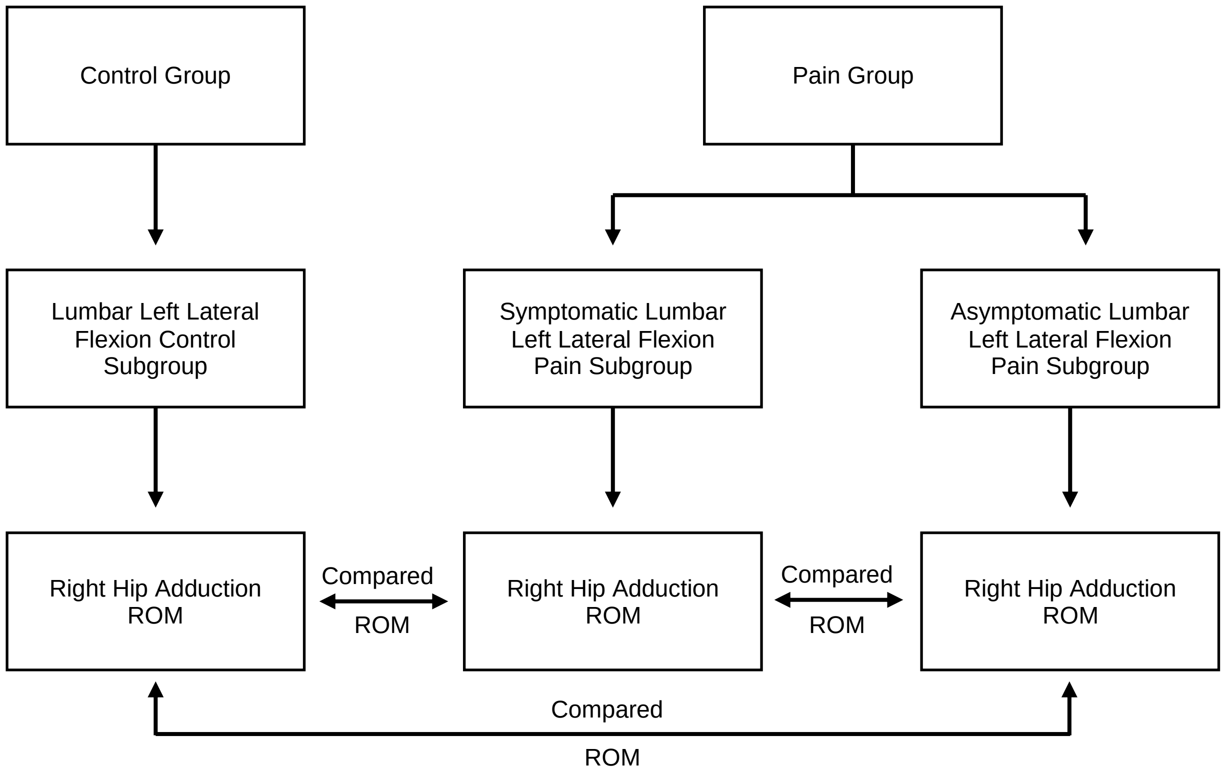

Fig. 3. 19 Schema illustrating the group splitting and hip adduction ROM sorting for the lumbar left lateral flexion-right hip adduction coupling's pairwise comparisons.

For the lumbar rotation-hip rotation coupling analysis, prone hip rotation's ranges were utilised as lumbar rotation takes place with the hip in sagittal plane neutral. When performing lumbar rotation, depending on the individual's acetabular and femoral version angles, either left, right or both hips' rotation ranges are capable of limiting the lumbar range. Therefore for example, left lumbar rotation is limited by left hip IR, right hip ER or both hips moving equally in concert. Consequently, each subgroup's participants were sorted depending on whether their left and right hip rotation ranges were equal, that is the hip IR and ER difference was ≤10º (Ellison et al., 1990); whether hip ER was greater than IR by more than 10º (retroverted hips) or whether hip IR exceeded ER by more than 10º (anteverted hips) (see Fig. 3.20 below). When a subgroup's participant's hip IR and ER's ROM was equal (when their difference was ≤10º), these two ranges were averaged, collated and their means compared for significance. In a similar procedure to what was demonstrated in left lumbar lateral flexion-right hip adduction above, the smaller hip rotation range was compared between the subgroups, if it was the limiting factor. For example, during left lumbar rotation's investigation, participants with retroverted hips' (as per definition in section 2.3.2 above) left hip IR ROM was compared across the subgroups, as it was the limiting hip range. Thus the participants were sorted into smaller subgroups, depending on the presence or absence of lumbar symptoms and their hip version characteristics; their pertinent hip rotation ranges were then collated and the means/medians compared for significance.

When a subgroup's sample size approximated 30 in number, Shapiro-Wilk analysis was used to ensure each subgroup's hip range mean's normality. Then the three subgroup's coupled hip ranges were compared for significance using a one way ANOVA. Levene's Test was utilised to ensure homogeneity of variance (its results were highlighted only when significant). As the three subgroups' size differed, Levene's test deemed non-significant, Hochberg's GT2 was employed for lumbar extension–hip extension; and right lateral flexion-left hip adduction post hoc pairwise comparisons (Freeman, 2020). Gabriel post hoc analysis was used in lumbar flexion-SLR investigation as the subgroup sizes varied only slightly. As the Levene Test's calculation was .030 with left lateral flexion-right hip adduction analysis, the Games-Howell test was used for post hoc analysis there (Freeman, 2020).

Since one of the subgroups had a small sample size (n = 9), lumbar flexion-hip flexion/squat coupling necessitated analysis with non-parametric, Kruskal-Wallis testing, as normality analysis was not possible. Similarly, the Kruskal-Wallis test was utilised in left lumbar rotation – left hip IR = right hip ER (ranges equal); left lumbar rotation – limited by left hip IR (left hip IR<right hip ER); right lumbar rotation - right hip IR = left hip ER (ranges equal) and right lumbar rotation - limited by right hip IR (right hip IR< left hip ER) because the small sample sizes here also voided normality testing. Left lumbar rotation, limited by right hip ER (left hip IR>right hip ER), and right lumbar rotation, limited by left hip ER (right hip IR> left hip ER), statistical analyses were not performed because the divided subgroups were either too small or did not have participants presenting with anteverted hips.

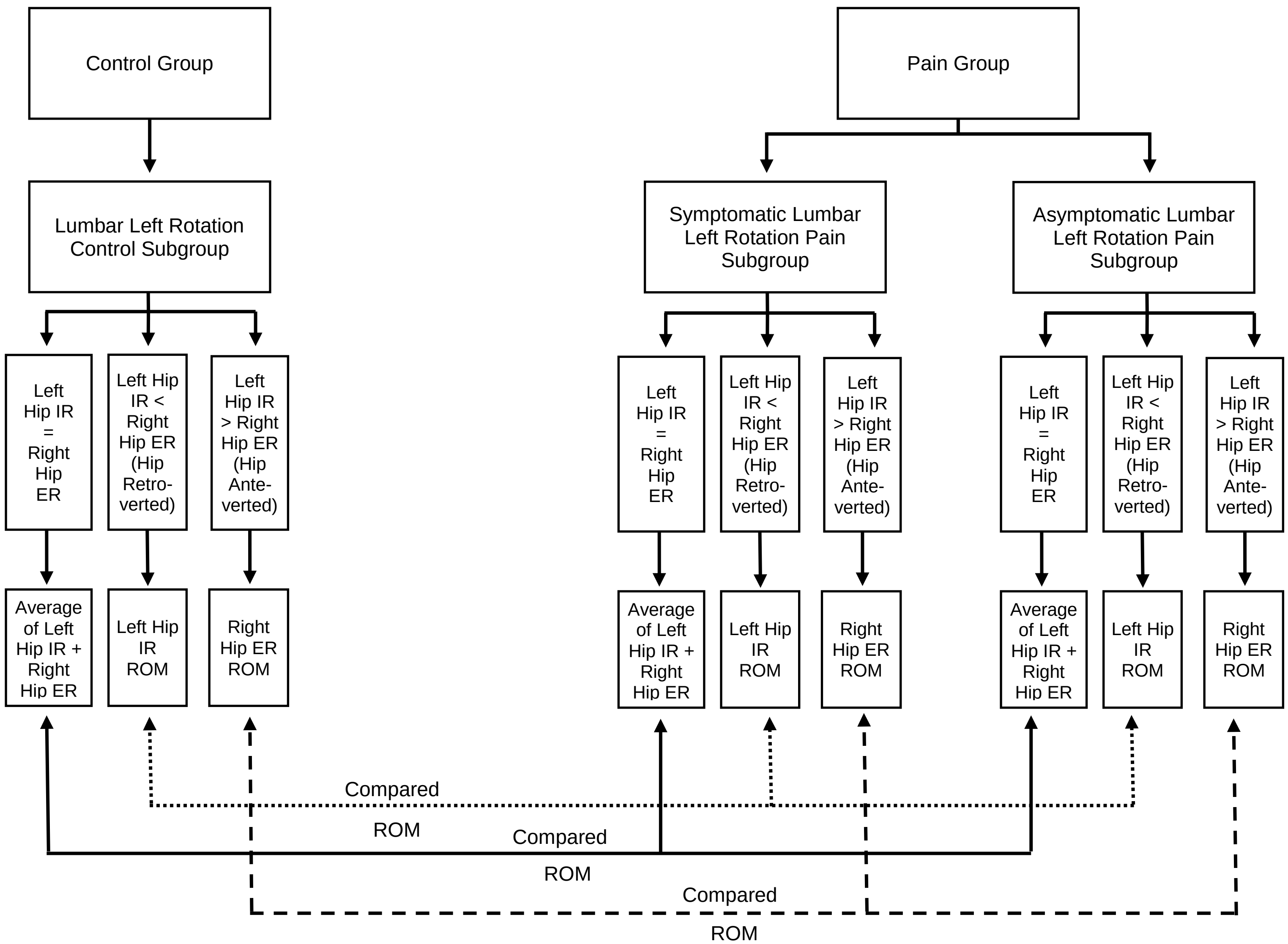

Fig. 3. 20 Schema illustrating the group splitting and hip rotation-pattern sorting for the lumbar left rotation-hip rotation coupling's pairwise comparisons.

3.8.4 Statistical Analyses Employed in Objectives 6 and 7 To Determine Whether Differing Sagittal Plane Positions Affect Hip Rotation ROM

For objectives 6 and 7, the whole cohort was utilised for the investigation on sagittal plane effects' on hip rotation ROM. The variables were not split into their grouping, enabling analysis of all 95 participants from both groups. A Shapiro-Wilk analyses was performed on this new sample to determine whether each variable was normally distributed. Since all the variables were found to be normally distributed and because hip rotation was being compared across three different sagittal positions in the same participants, a repeated-measures one-way ANOVA was utilised for the analysis. Significance levels were adjusted with a Bonferroni correction.

3.8.5 Statistical Analyses Employed in the Reliability Studies

Test-retest reliability study analysis was performed on 10 participants. The statistical analysis was performed on MTT unadjusted, SLR results. A "two-way mixed" model and "absolute agreement" type settings were utilised. The Cronbach's alpha and 95% confidence intervals are quoted below in Table 25.

Chapter 4 Validation Studies

4.1 Introduction

Traditionally joint ROM measurement was achieved with goniometers and inclinometers. Obtaining precise results from these devices can be challenging. It has been suggested that a change of at least 7º was necessary to accurately detect a real change in joint range (Roach and Miles, 1991). Formerly, researchers (Ellison et al. 1990; Ellenbecker et al. 2007; Moreno-Perez et al. 2016) reliant on inclinometers, goniometers and digital imaging and angle calculation software deemed joint angle differences of less than 10º equal, attributing this to measurement error. As certain hip ranges could be as little as 10º, drawing reliable conclusions from data making use of this margin of error proved difficult. Biomechanical science has been able to obtain increasingly more accurate measures since those earlier times. This research, benefiting from these technological advances, made use of wearable, wireless IMU's to measure the hip's ROM. They offer a precise, convenient and unobstructed approach to joint ROM measurement.

The integration of an IMU's three tools, namely the accelerometer, magnetometer and gyroscope, enables greater accuracy than when used individually (O'Reilly et al., 2018). The accelerometer and magnetometer determine "linear acceleration" and "heading reference" respectively (Anon., 2020), while the gyroscope calculates angular velocity (Luinge and Veltink, 2005). Gyroscopes permit instant movement detection but when tracking over a period of time, measurement inaccuracies accumulate resulting in a phenomenon known as gyroscope drift (El-Gohary and McNames, 2015; Luinge and Veltink, 2005; Anon., 2020; Wittmann et al., 2019). Potential errors on the gravity-influenced x and z-axes are corrected by integrating the accelerometer's measurements with those of the gyroscope (Wittmann et al., 2019). Drift errors, however accrue and are seemly most pronounced around the y-axis (El-Gohary and McNames, 2015; Wittmann et al., 2019). Since gravity is rendered inconsequential in the horizontal plane, sensor accuracy deteriorates when there is little or no acceleration during periods of slow or static movement, this is because angle measurement would now be reliant solely on the gyroscope's capability (El-Gohary and McNames, 2015). Since the earth's magnetic field does not act in parallel with this vertical axis, magnetometers are integrated with gyroscopes to adjust these measurements (Wittmann et al., 2019). Although this integration improves functionality, magnetic field disturbances caused by the ferromagnetic materials in a room's furniture, walls, floor and ceiling still affects an IMU's performance (Wittmann et al., 2019; El-Gohary and McNames, 2015), with 15º measurement errors being reported after just a few minutes of use (Wittmann et al., 2019). Algorithms, called Kalman filters, have been developed to correct for magnetic interference, however accuracy diminishes with the presence of "varying [ferromagnetic] sources that are present during longer periods of testing" (El-Gohary and McNames, 2015, page 1759).

4.2 The Concurrent Validity of IMUs, Robotic Systems and Optoelectronic Motion Capture Systems

Different devices in the marketplace, each consisting of unique hardware and software, exhibit differing degrees of accuracy. For contextual and comparative purposes, studies examining IMU validity against "gold standard" technologies, such as various optoelectronic and robotic systems, were reviewed. In 2010 Cuesta-Vargas et al. conducted a systematic review of the human movement measurement literature weighing a variety of IMU's against different gold standard devices. Although directly referencing each product, they unfortunately did not always list each sensor's components. They concluded that a reliability error of 2º or less was acceptable; errors between 2º and 5º were "reasonable" but could require attention when analysing results; and errors of greater than 5º were of a concern and nature that would misinform clinical judgement (Cuesta-Vargas et al., 2010).

Bolink et al. (2015) compared the pelvic orientation angle measurements of a "gold standard" optoelectronic motion capture system with a single sensor IMU (consisting of tri-axial accelerometers, gyroscopes and magnetometers) during three activities-of-daily-living, namely gait, sit-stand and step-up transfers. The data was captured simultaneously from both devices during these tasks. Frontal plane pelvic movement measurements attained a root mean square error range of 2.7° to 4.5° with a 2.7° to 8.9° range in the sagittal plane; the wave peak detection times showing an ICC of 0.96 to 1.00.

Another study comparing six purposefully placed IMU's to an optical tracking system, weighed its performance using 49 participants who had received total hip replacements (Zügner et al., 2019). They examined sagittal plane motion of the pelvis, hip and knee during the gait cycle using a pressure plate to synchronise the two measurement systems. Regretably, their IMU system, only consisting of gyroscopes and accelerometers, did not measure angles in the transverse plane. As a result this functionality was not evaulated by their study. They found no significant difference between the devices at the pelvis and knee, however the IMU's hip flexion/extension results were approximately 3° lower ($p < 0.001$) than those of the optical system. They attributed this to soft tissue artefact, differing alignment of the two system's markers, inadequate positioning of the IMU's sensors and different pelvic modelling software.

Evaluating IMU performance against that of a "high-precision robotic arm", advantageously negates soft tissue artefact and simplifies sensor placement (El-Gohary and McNames, 2015). They attached single IMUs to each segment of a robotic arm and compared their performance at three different speeds, 180°/second, 360°/second and 720°/second. Over a 15 minute time period, the IMUs were repeatedly sequenced through six isolated planar ROM around the different robotic joints, a one second stationary period and then a more complex, combined multi-joint motion. Instead of incorporating a magnetometer, a Kalmin Filter recalibrated the gyroscope during static periods. At the slowest speed, the average difference between the devices, for all the tested joint ranges, was less than or equal to 3°, with the greatest error of 7.8° ocurring around the vertical axis. Notably, these errors accrued after 15 minutes of motion and may have been complicated by table vibration on which the robot was mounted.

More recently, Robert-Lachaine et al. (2017) made use of functional tasks to compare Xsens IMU's and an optoelectronic system over a 32 minute testing period. Even though they concluded that some caution should be taken when comparing the systems, the differences were still below 5^{o}.

4.3 The Rationale for Validity Testing

As a sensor's level of reliability appears to be locale specific (Cuesta-Vargas et al., 2010) and since this particular IMU (Shemesh Health Solutions Pty Ltd, Johannesburg, South Africa) had not been previously used in hip ROM research, a series of validity tests were undertaken to identify any potential performance pitfalls. This also proved necessary, as this IMU had not been validated in the 60^{o}-to-horizontal plane before. O'Reilly et al.'s (2018) systematic review's recommendation for further research to investigate the validity of single IMU assembly in lower limb joint angle measurement was another consideration. Consequently, each hip range's measurement demands was analysed and its components determined. The IMU's spirit level and angle measurement function were then tested in these conditions to determine their accuracy and expose any gyroscope drift.

Validity studies were conducted with the following aims:

- **Validation study 1:** to determine the ability of the IMU's spirit level function to find horizontal in a vertical plane in its upright and inverted positions.
- **Validation study 2**: to determine the ability of the IMU's spirit level function to find horizontal in a 60^{o}-to-horizontal plane.
- **Validation study 3**: to determine whether the IMU's spirit level function displayed gyroscope drift when passing through a 60^{o}-to-horizontal plane.
- **Validation study 4**: to determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the frontal plane.

- **Validation study 5**: to determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the sagittal plane in the upright position.
- **Validation study 6**: to determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the sagittal plane in the inverted position.
- **Validation study 7**: to determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the transverse plane through the "u" arc of motion in the upright position.
- **Validation study 8**: to determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the transverse plane through the "n" arc of motion in the inverted position.
- **Validation study 9**: to determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the transverse plane through the "n" arc of motion in the upright position.
- **Validation study 10**: to determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the 60º-to-horizontal plane through the "u" arc of motion in the upright position.
- **Validation study 11**: to determine whether the IMU's spirit level angle measurement function performed accurately and experienced gyroscope drift in the transverse plane, comprising two different arcs of motion, and in the 60º-to-horizontal plane.

4.4 Experimental Setup

The sensor's accuracy was validated against a goniometer (Baseline, Fabrication Enterprises Inc. White Plains, New York) and bubble spirit level (Ross Measuring Tools, model LL8, Yongkang Wanxin Industry and Trade Company, Zhejiang Province, China). The IMU was mounted on the goniometer's mobile arm. To ensure it was properly aligned, the sensor's sides were measured with a metal ruler to determine their midpoints and then mounted on the Perspex arm using these axes.

The flat surface of the sensor was attached to the goniometer ensuring that the ridges on the casing did not affect the readings. The manufacturers had instructed the author that the IMU's casing's shorter length was its upper side; the term "upright" is stated in the ensuing paragraphs when this side was uppermost.

The sensor validity studies required a flat, square, robust and moveable mounting surface. A large floor tile was deemed appropriate. The tile was examined to ensure it was square in the following way. A goniometer was used to verify the 90^{o} angle of a metal try-square (Fig. 4.1A) and then each tile corner was validated against the try-square (Fig. 4.1B). All images presented in this chapter are available in a higher resolution for the reader's perusal at www.dropbox.com (email/account: kermann@tiscali.co.za ; password: research123). A flashlight was shone from below to ensure that the try-square and tile's corners were flush. Every corner was verified to be 90^{o}. To test whether the tile's sides were perfectly straight, a bubble spirit level (Ross Measuring Tools, model LL8, Yongkang Wanxin Industry and Trade Company, Zhejiang Province, China) was placed against each side (Fig. 4.1C). This was found to be the case.

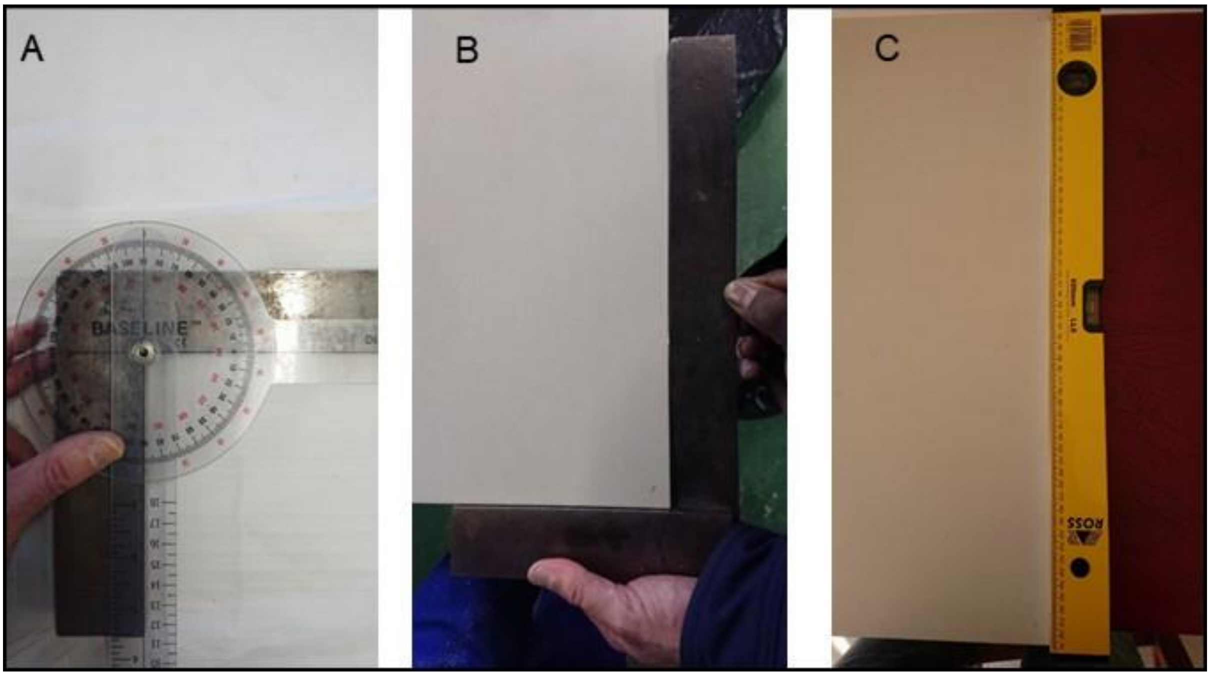

Fig. 4. 1 A) Verifying the metal try-square's accuracy against a goniometer. B) Testing whether a tile's corner was a right angle with the metal try-square. C) Ensuring the tile's sides were straight using a bubble spirit level.

Magnetometers are prone to measurement inaccuracies in the presence of "ferromagnetic materials" (Luinge and Veltink, 2005). Metal furniture was therefore avoided; the testing was conducted on either a wooden table or a granite kitchen top. Audenaert et al., (2011) using an electromagnetic sensor and not an IMU, reported that testing performed less than a metre from a steel reinforced concrete floor could create distortions in a sensor's outcomes. Unfortunately, both of these benchtops were below that height, it is uncertain whether this had an impact on the accuracy of the results.

4.4.1 Validation Study 1

Aim: To Determine the Ability of the IMU's Spirit Level Function to Find Horizontal in a Vertical Plane in Its Upright and Inverted Positions

First, the IMU's spirit-level was assessed through two validation tests. The sensor's spirit-level horizontal functionality was tested against a bubble spirit-level and demonstrated a high level of accuracy. Placed upright on top of the perfectly horizontal bubble spirit-level, the IMU's application displayed a 1^o reading (Fig. 4.2A). When the IMU was inverted on top of the level, the application displayed a 0^o, perfectly horizontal reading (Fig. 4.2B). This test proved that the IMU's spirit level accurately identifies perfect horizontal, and thereby vertical, in the upright and inverted positions.

Fig. 4. 2 A) IMU in the upright position with application's spirit level function operating in the background. B) IMU in the inverted position.

4.4.2 Validation Study 2

Aim: To Determine the Ability of the IMU's Spirit Level Function to Find Horizontal in a 60^o-to-Horizontal Plane

Now that the spirit-level function was validated in the vertical plane, it was necessary to confirm whether it could identify the horizontal when moving through a plane pitched at a 60^o angle. To prove this functionality's accuracy the sensor had to be moved along the same surface pitched at a 90º (vertical) and 60º angle. A pencil line was plotted, on a piece of confirmed square cardboard paper, parallel to its edge. The cardboard paper was mounted on the corner of the square floor tile. Verified with a bubble spirit-level the tile was then propped perfectly vertically against a wall (Fig. 4.3A, Fig. 4.3B and Fig. 4.3C).

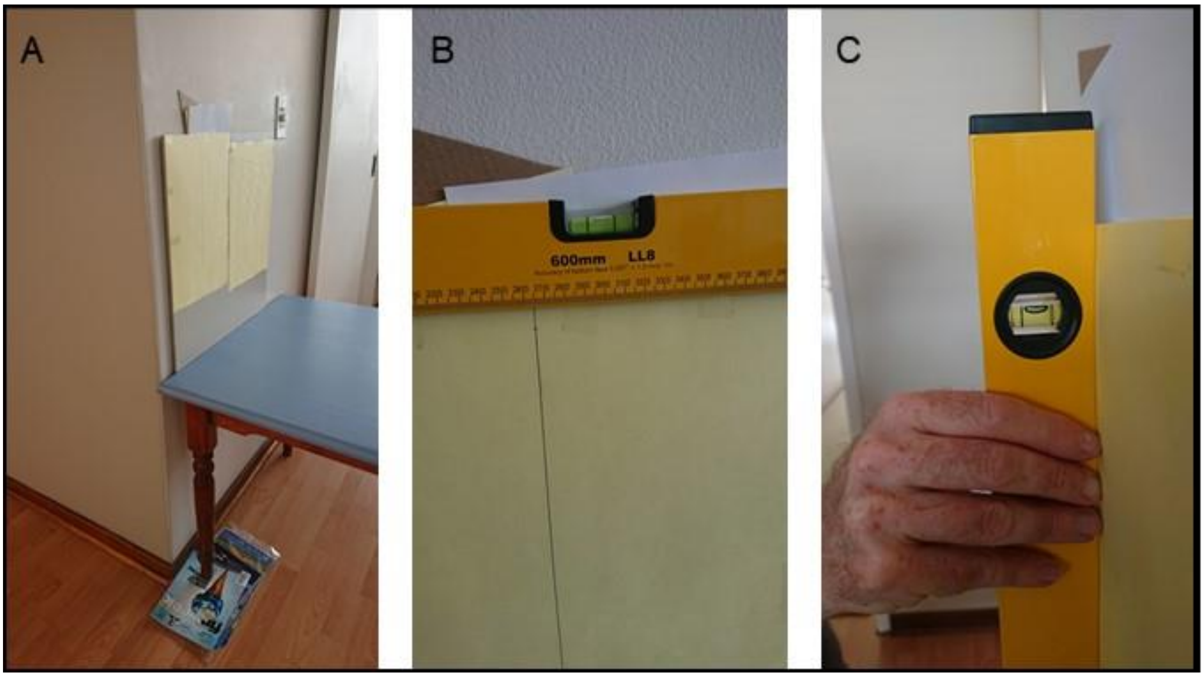

Fig. 4. 3 A) Tile propped up vertically against a wall. B) Confirmation using a bubble spirit level that the upper edge of the tile was horizontal. C) Confirmation with bubble spirit level that the tile's surface was vertical.

The sensor was lined up against the pencilled line, where the application's spirit level's 0º reading confirmed (Fig. 4.4A) it was perfectly vertical (as the sensor's lower surface was horizontal). When the sensor was moved off the pencilled line, the application's reading changed to 20º (Fig. 4.4B).

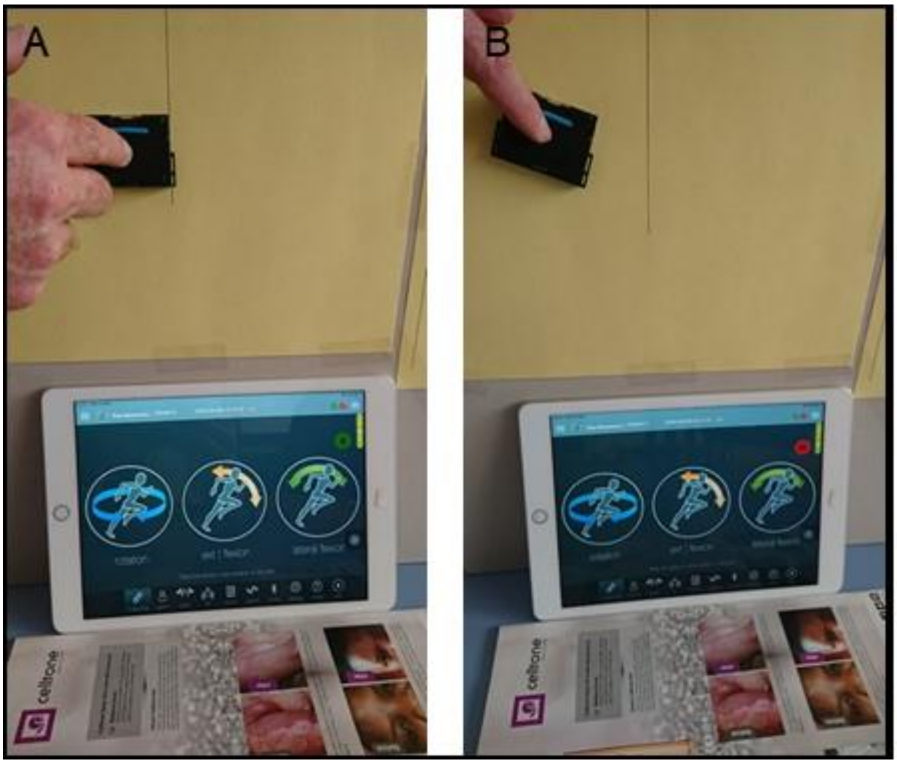

Fig. 4. 4 A) Sensor placed on the vertical line, identifying vertical. B) Sensor displays a new reading once moved off the vertical axis.

The floor tile was then inclined against the wall at a 60º angle guided by a true opaque 60º cardboard triangle and bubble spirit level (Fig. 4.5A, Fig. 4.5B and Fig. 4.5C).

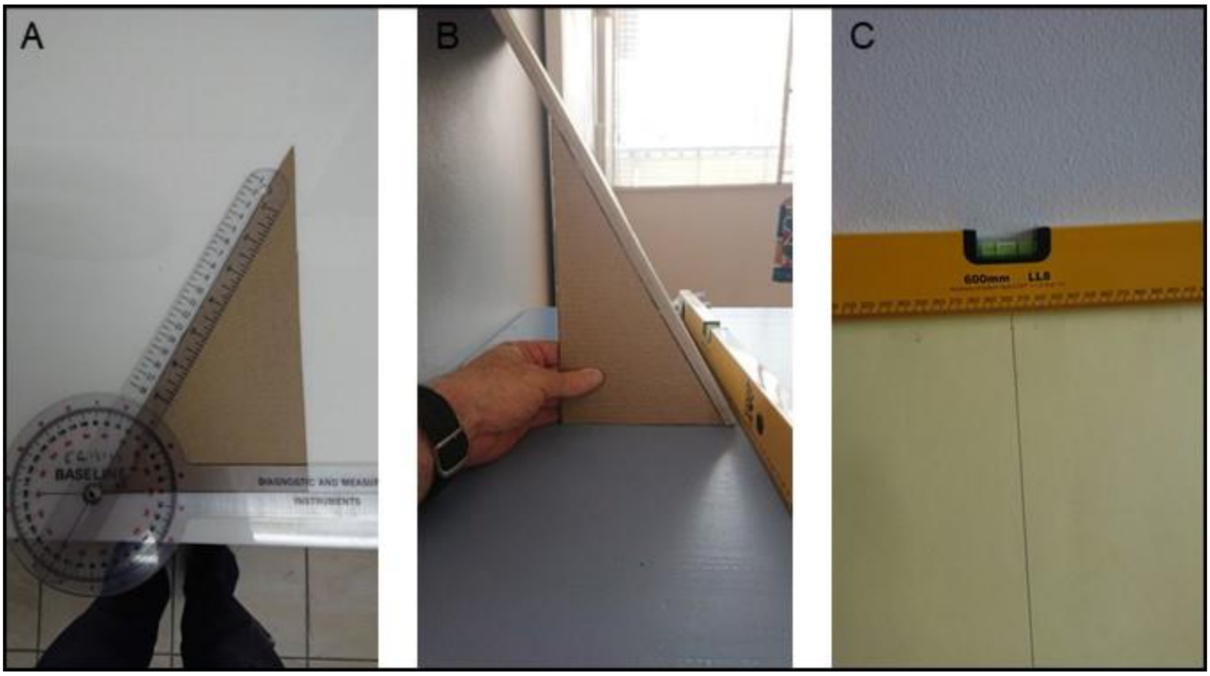

Fig. 4. 5 A) Confirmation that the cardboard triangle's angle was 60º. B) Tile aligned at a 60º pitch. C) A bubble spirit level indicating that the upper edge of the tile was horizontal.

The IMU was once again placed against the same pencilled line (Fig. 4.6A). The application's spirit level function again displayed a 0º angle (Fig. 4.6B), indicating its reliability in identifying perfect spirit level horizontal when pitched at a 60º angle. This was confirmed once again, when the device was moved off the pencilled line, where it displayed a different reading, 18º (Fig. 4.6C). This test proved that the sensor could identify spirit-level horizontal when moving through a 60º angled plane.

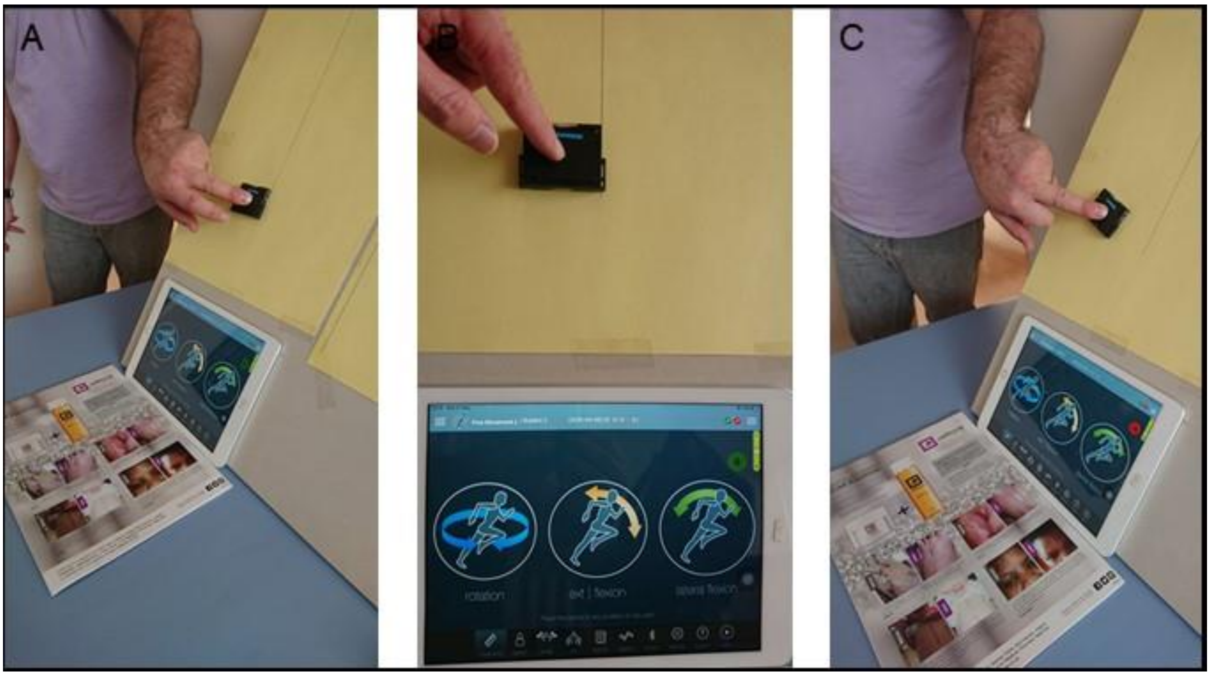

Fig. 4. 6 A) Demonstrating that the IMU detects vertical in the 60º-to-horizontal plane. B) Close-up of the application's display with IMU on the pitched vertical line in the background. C) The application's spirit level function displays a new reading once moved off the vertical line.

4.4.3 Validation Study 3

Aim: To Determine Whether the IMU's Spirit Level Function's Ability to Find Horizontal in a 60º-to-Horizontal Plane, was Affected by Gyroscope Drift

An additional test, to validate the sensor's spirit level function and determine whether it was affected by gyroscope drift when moving through a 60º plane, was also carried out. Pencil marks were made on the tile at two points 15 cm from one side, and then joined together creating an axis for the goniometer to be mounted on. The floor tile was pitched at a 60º angle, verified in the same manner as before. The sensor was mounted to the goniometer's mobile arm (Fig. 4.7A) and the stationary arm was secured to the tile on the pencilled line (Fig. 4.7B).

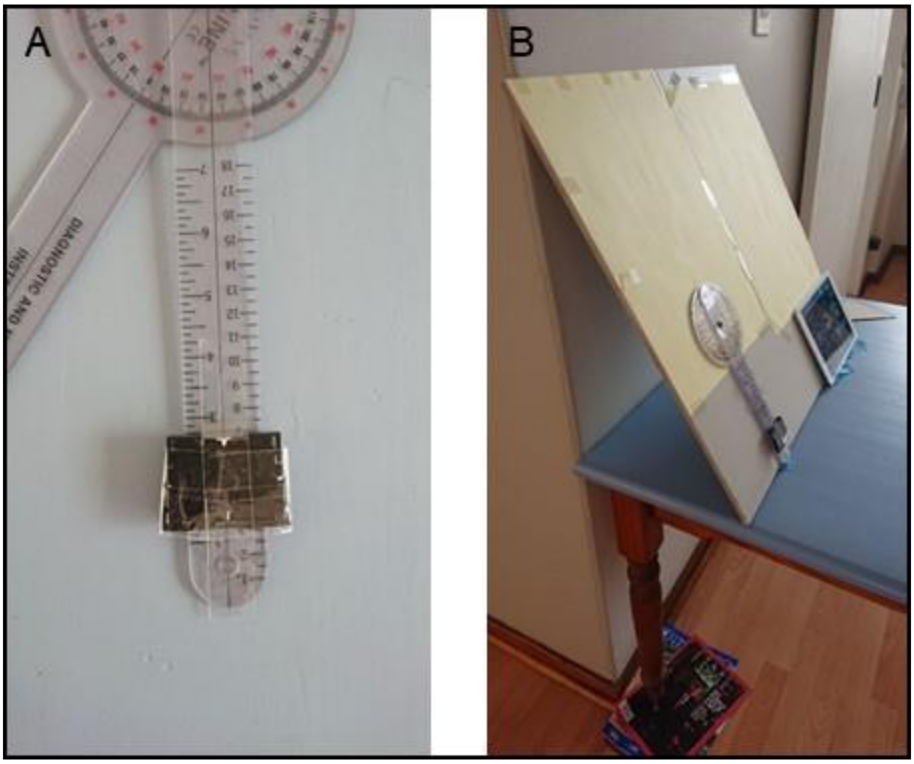

Fig. 4. 7 A) The IMU's mid-points aligned and mounted on the goniometer's mobile arm's axis. B) The goniometer's stationary arm mounted on the pitched tile's pencilled axis.

The application's spirit level function was activated with the goniometer's mobile arm in the vertical, 0º position. The application showed a 0º reading (Fig. 4.8A). The mobile arm (and sensor) were then moved to the 80º point to the left and right side of the goniometer, moving through the 0º point 10 times, 5 times to each side. The mobile arm was then returned to the goniometer's 0º mark, where the application displayed a 0º reading (Fig. 4.8B). Once again the sensor proved, when pitched at a 60º angle, it was accurate finding the perfectly horizontal mark (and thereby vertical mark) and confirmed that gyroscope drift was absent.

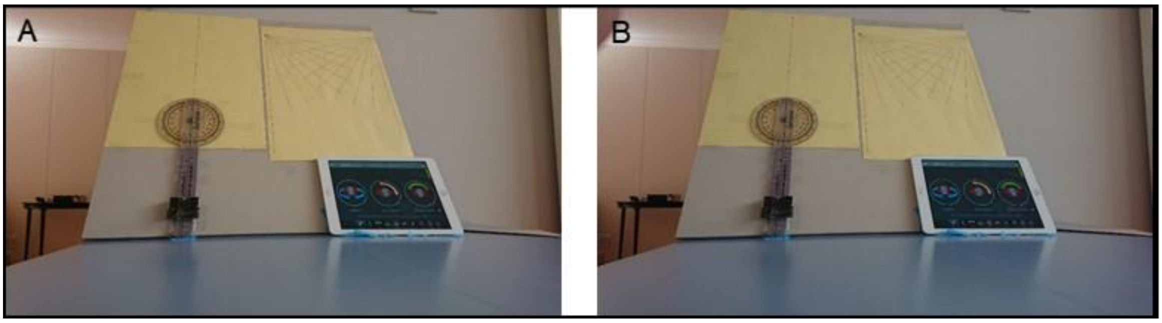

Fig. 4. 8 A) At the start of the test the application's spirit level function was activated and displayed a 0º reading. B) At the end of the test, after moving the mobile arm and sensor, it displayed a 0º reading, accurately finding the starting position.

The IMU's angle measurement function was then tested. It was assessed for accuracy and gyroscope drift in all planes required in the study.

4.4.4 Validation Study 4

Aim: To Determine Whether the IMU's Angle Measurement Function Performed Accurately and Experienced Gyroscope Drift in the Frontal Plane

The sensor's angle measurement functionality was tested in the frontal plane by mounting it on the goniometer's mobile arm, the stationary arm in turn, was secured to a horizontal counter top. After calibration, the sensor was moved 10 times in a clockwise and anti-clockwise direction, through its starting point 20 times, to the 70º points. The sensor was then returned to the 0º point and moved progressively to different markers. It accurately located multiple points, never being more than a degree out in the clockwise direction (Fig. 4.9A and Fig. 4.9B), but underwent gyroscope drift when moved anti-clockwise, showing a 6º error in certain positions (Fig. 4.9C). See Table F1 in Appendix F for detailed results.

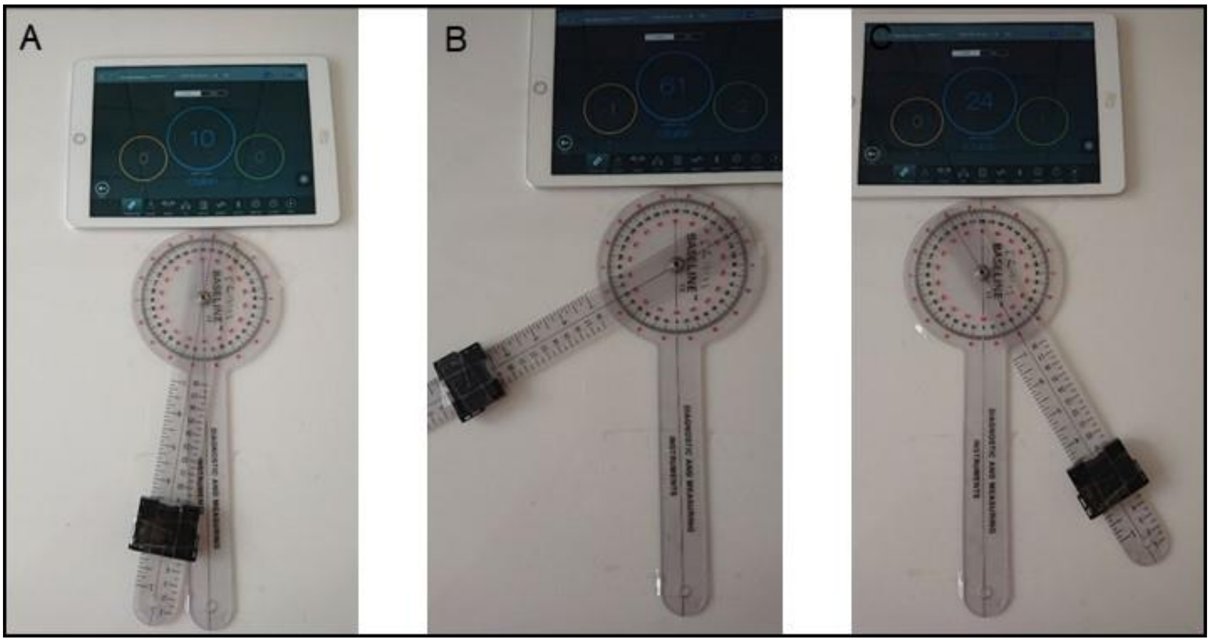

Fig. 4. 9 A) The application accurately displays the 10º point in the clockwise direction. B) The application shows a 1º error, displaying 61º at the 60º marker in the clockwise direction. C) The sensor experiences gyroscope drift in the anti-clockwise direction, displaying a 24º reading at the 30º marker.

The same test was then repeated moving the sensor through the starting point 10 times. This time the sensor fared better, locating the test angles within a degree in both clockwise (Fig. 4.10A) and anti-clockwise direction (fig. 4.10B) but it did not accurately find the starting point in this trial, displaying a 3º error (Fig. 4.10C). See Table F2 in Appendix F for detailed results.

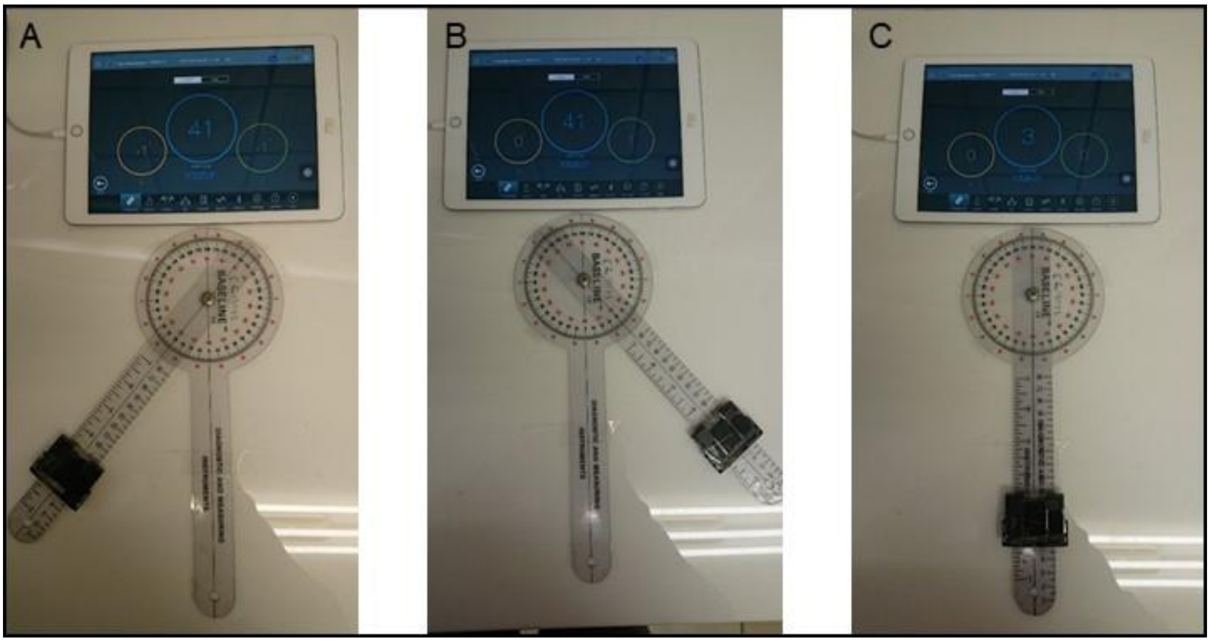

Fig. 4. 10 A) The application displays a 41º reading at the 40º point in the clockwise direction. B) The application presenting a 41º reading at the 40º marker in the anti-clockwise direction. C) The application exhibiting a 3º reading on return to the 0º starting point.

When comparing these two tests, gyroscope drift in the frontal plane was clearly confirmed. The sensor was accurate in measuring an angle once though. After calibration and moved to a specific position in either the clockwise (Fig. 4.11A), neutral (Fig. 4.11B) or anti-clockwise direction (Fig. 4.11C), it displayed a maximum 1º error.

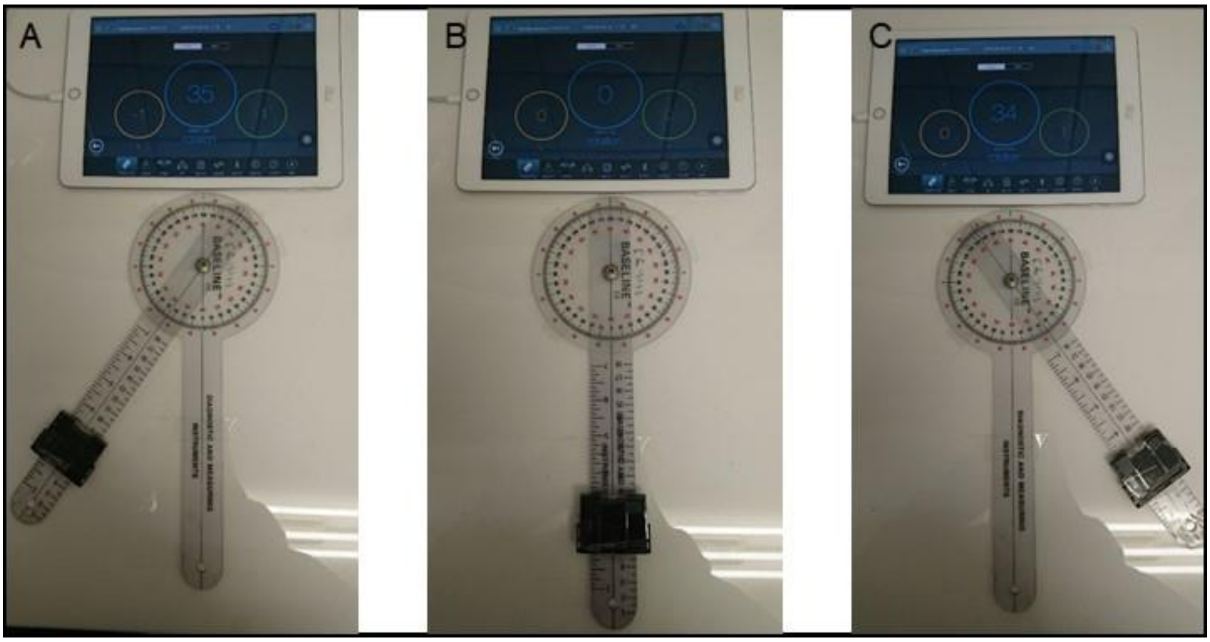

Fig. 4. 11 A) The application displays a 35º reading at the clockwise 35º point. B) The application accurately exhibits a 0º reading on return to the starting point. C) The application shows a 34º reading at the anti-clockwise 35º marker.

However, the sensor performed inconsistently in a test to determine accuracy and gyroscope drift in conditions resembling those proposed in the study. The sensor was calibrated and then moved to the 35º mark and oscillated at this marker, paused over the point and then returned to the 0º starting position. The tester then waited a few seconds and then repeated the process two more times. The sensor performed well in the clockwise direction, perfectly locating the end point each time and displayed a 1º error on return to the starting point, however demonstrated gyroscope drift in the anti-clockwise direction. Here, on the third measurement, there was a 3º error locating the 35º mark and 4º miscalculation on return to the 0º starting point. Videos MOV_1959 and MOV_1958 capturing this test are available on request.

In conclusion, varying angle measurement errors presented in the frontal plane as a result of gyroscope drift. Consequently, before each and every abduction and adduction trial the sensor's (and hip's) starting position was reset by an extendable goniometer and the application recalibrated.

4.4.5 Validation Study 5

Aim: To Determine Whether the IMU's Angle Measurement Function Performed Accurately and Experienced Gyroscope Drift in the Sagittal Plane in the Upright Position

The first test of the sensor's angle measurement functionality for the sagittal plane in the upright position followed a similar methodology. The sensor was mounted on the goniometer's mobile arm in the upright position. It was calibrated in the horizontal and then moved 10 times from the 0º to the 160º position. The arm was then returned to the 0º mark and readings were taken incrementally at each 10º point, between 0º and 160º. There was never more than a 1º error for all the acute (Fig. 4.12A) and obtuse angles (Fig. 4.12B) tested. See Table F3 in Appendix F for detailed results.

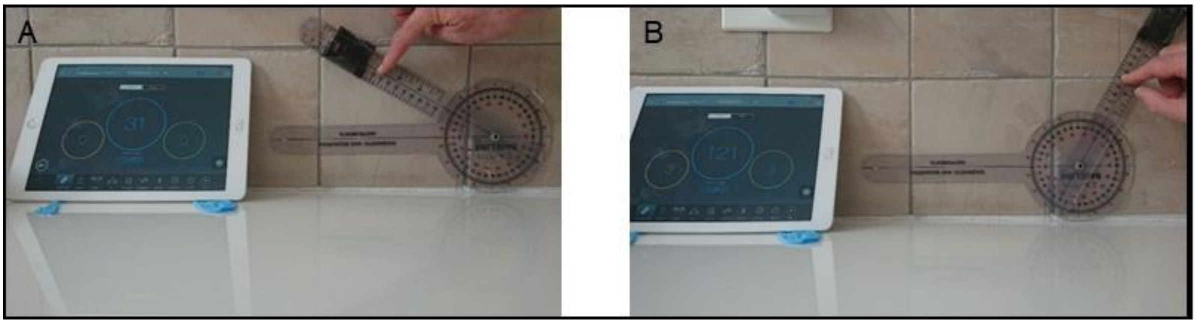

Fig. 4. 12 A) The application demonstrates a 31º reading at the 30º point. B) The application exhibits a 121º reading at the 120º marker.

In a second test, to assess its ability to find the starting point, it was calibrated and then passed through the same 160º range 10 times. There was 1º fault on return to the starting position (Fig. 4.13A). It was also accurate to the degree when lowered below the starting point, but didn't register a negative value below the horizontal (Fig. 4.13B).

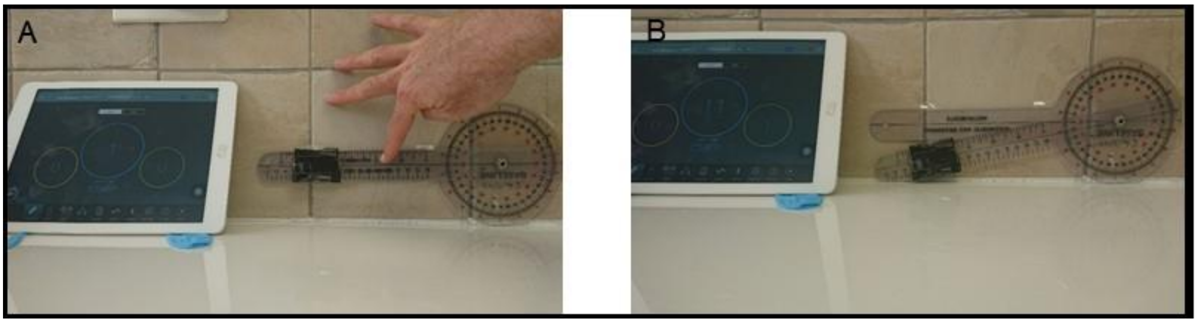

Fig. 4. 13 A) The central blue display demonstrating a 1º reading on return to the 0º starting point. B) The application displaying an 11º reading on reaching the -11º point below the horizontal.

In a third test, making use of the sensor's spirit level and angle measurement functionality, pilot research conditions were reproduced. The IMU was left in place, mounted on the goniometer's mobile arm. The IMU's spirit level was used to confirm the horizontal starting position and the angle measurement function calibrated. The stationary arm and sensor were passed through to the 120º mark three times, where it was oscillated over the endpoint. Between each cycle, it was rested twice beneath the starting point for a short period. Finally, it was returned to the starting position. Here again the IMU demonstrated an accuracy to 1º in identifying both the start and end-points. Video MOV_1962 capturing this test is available on request.

In the sagittal plane and upright position, the sensor's angle measurement functionality proved its accuracy and absence of gyroscope drift. Since the sensor's angle measurement function repeatedly and accurately located the starting position, a single calibration was used in sagittal plane range measurement.

4.4.6 Validation Study 6

Aim: To Determine Whether the IMU's Angle Measurement Function Performed Accurately and Experienced Gyroscope Drift in the Sagittal Plane in the Inverted Position

Initially, the intention was to perform hip flexion and extension range measurements with the sensor secured in the same position on the participant's thigh. Validity testing of the angle measurement functionality with the sensor in an inverted position was therefore necessary. The sensor was left in position from the "flexion" range testing above, namely, taped to the mobile arm of the goniometer. The instruments were turned over and the goniometer's stationary arm fixed to the wall in the horizontal. The sensor was calibrated at the 0º mark and then the mobile arm was moved 10 times through a 60º angle in keeping with hip extension ranges. Thereafter, the sensor was returned to the starting point and readings were taken at different increments. There was a 1º discrepancy at the 10º and 20º marks (Fig. 4.14A); a 2º discrepancy at the 30º, 40º and 50º points (Fig. 4.14B) and 3º discrepancy at the 60º mark (Fig. 4.14C), with a 1º disagreement on return to the starting point (Fig. 4.14D). See Table F4 in Appendix F for detailed results.

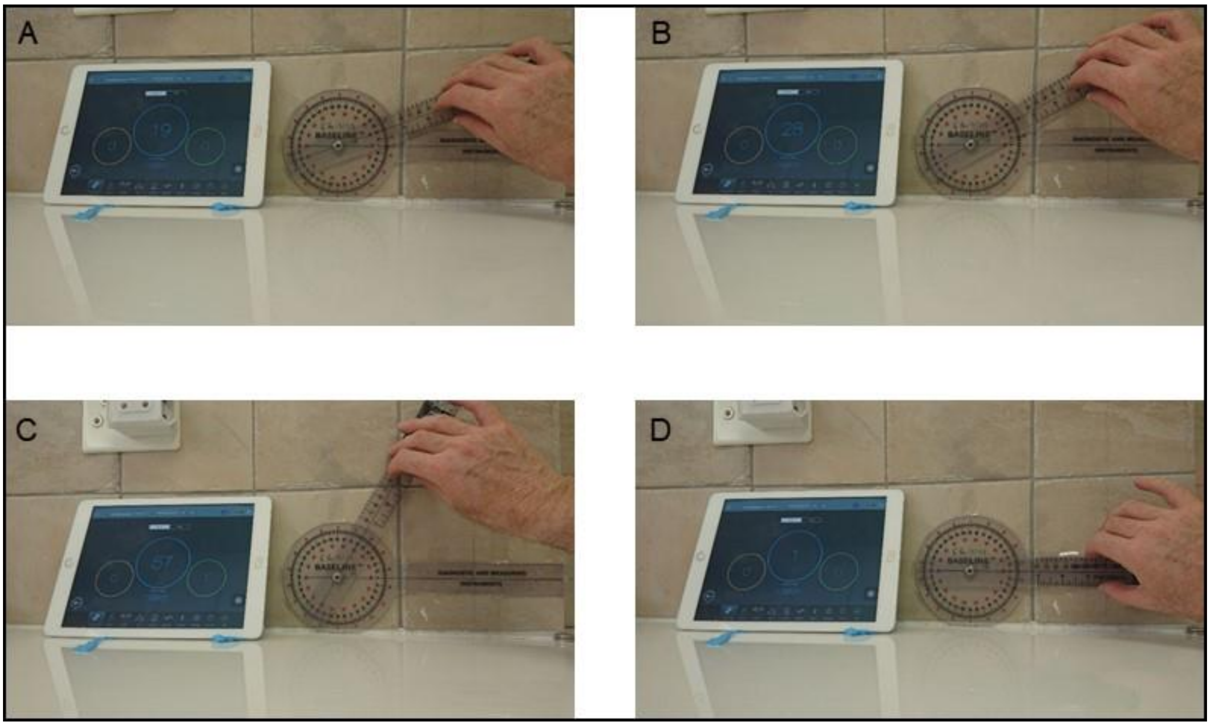

Fig. 4. 14 A) The application shows a 19º reading at the 20º marker. B) The application demonstrates 28º at the 30º point. C) The application registers 57º at the 60º end point. D) The application displays 1º on return to the 0º starting position.

To determine whether these inaccuracies, in the inverted position, were due to the sensor's position or gyroscope drift, the sensor was moved once to a specific angle. The sensor was calibrated at the 0º position and then moved to the 25º mark. There was a 2º error at this marker (Fig. 4.15A) and again, 1º discrepancy on return to the starting position (Fig. 4.15B).

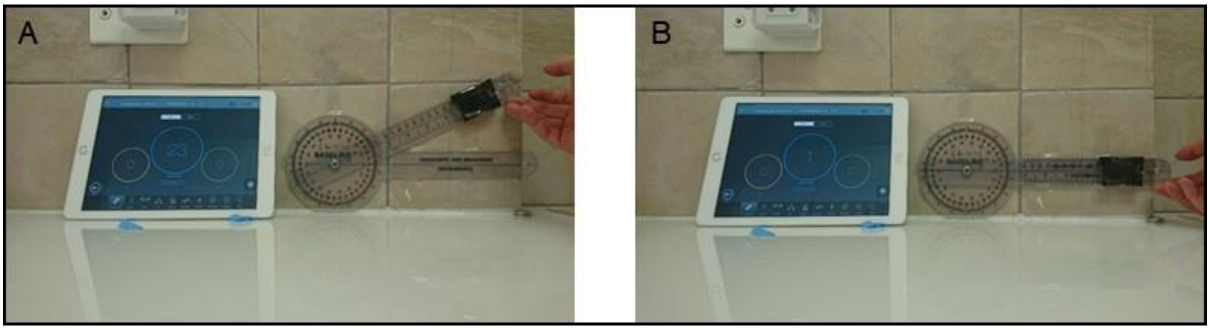

Fig. 4. 15 A) The application displays a 23º reading at the 25º point. B) A 1º reading at the 0º starting position.

To conclude, the sensor's angle measurement function did not suffer gyroscope drift in the inverted position in the sagittal plane but displayed 1º to 3º inaccuracies, depending on the chosen angle. Due to the inverted sensor's inaccuracies above 20º, the researcher chose to resite the sensor right side up for hip extension and rotation testing.

4.4.7 Validation Study 7

Aim: To Determine Whether the IMU's Angle Measurement Function Performed Accurately and Experienced Gyroscope Drift in the Transverse Plane Through the "u" Arc of Motion in the Upright Position

The sensor was tested in the upright position for the transverse plane, through the "u" arc of motion, to ensure its angle measurement functionality and identify any gyroscope drift during hip rotation ROM measurement in the sitting position. The IMU was taped to the mobile arm of the goniometer on its midpoint lines, right-side up in keeping with the orientation of the sensor in human testing. The flat side of the sensor was mounted on the mobile arm, to ensure that the ridges on the sensor's casing didn't affect the reading. The goniometer's stationary arm was then mounted perfectly vertical on a wall. The sensor was calibrated at the 0º mark and the goniometer's mobile arm was then moved 10 times (5 times in each direction through the 0º mark) through to the 80º positions. Thereafter, it was returned to the starting point and moved clockwise: readings were taken at each 10º increment. There was never more than a 1º error at each point (Fig. 4.16A), on return to the starting point, it registered a 1º fault (Fig. 4.16B). Without recalibrating, it was then moved anti-clockwise to different positions. Here, there was never more than a 1º error at each position (Fig. 4.17A) with the exception of the 80º mark, where it was 2º amiss (Fig. 4.17B). On return to the starting position, there was once again a 1º discrepancy. See Table F5 in Appendix F for detailed results.

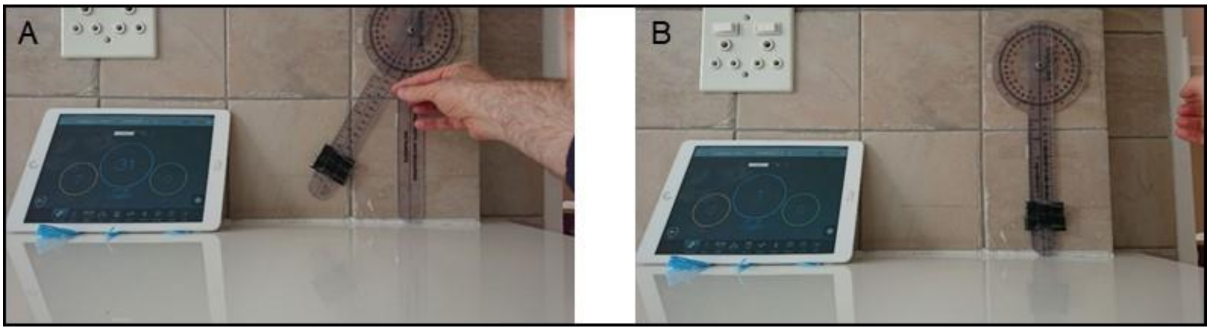

Fig. 4. 16 A) The application demonstrates a 31º reading at the clockwise 30º position. B) A 1º reading displays on return to the 0º starting point.

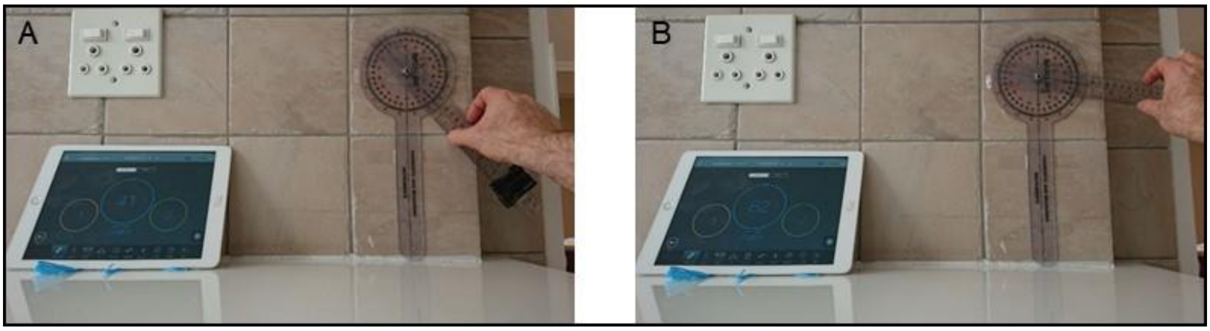

Fig. 4. 17 A) The application displays 41º at the anti-clockwise 40º marker. B) An 82º reading is displayed by the application at the 80º position.

To conclude, the IMU's angle measurement functionality proved accurate and displayed no gyroscope drift in the transverse plane, through the "u" arc of motion, when in the upright position.

4.4.8 Validation Study 8

Aim: To Determine Whether the IMU's Angle Measurement Function Performed Accurately and Experienced Gyroscope Drift in the Transverse Plane Through the "n" Arc of Motion in the Inverted Position

Initially, the intention was that the sensor remain in situ for all three hip rotation testing positions. This required testing for the transverse plane with sensor inverted (with participant positioned prone). To test its transverse plane angle measurement accuracy and gyroscope drift vulnerability through the "n" arc of motion and in the inverted position; the goniometer with sensor affixed to the mobile arm (as per Validation Study 7), was then overturned and mounted vertically on the wall along the same pencilled line. The IMU was calibrated at the 0^{o} mark and then the goniometer's mobile arm was moved 10 times (5 times in each direction through the 0^{o} mark) to the two 80^{o} endpoints. Thereafter, it was returned to the starting point and then moved anti-clockwise where readings were taken at each 10^{o} increment. There was a 1^{o} discrepancy at the 10^{o} and 20^{o} positions (Fig. 4.18A). There were 2^{o} errors at the 30^{o}, 40^{o} and 50^{o} points (Fig. 4.18B), while displaying a 3^{o} fault at the 60^{o}, 70^{o} and 80^{o} marks (Fig. 4.18C). It was then returned to and perfectly identified the starting point (Fig. 4.18D). Without recalibrating, it was then moved clockwise in 10^{o} increments. It was never more than a degree out at each point (Fig. 4.19A and Fig. 4.19B). Again, on return to the starting point the application displayed a 0^{o} reading. See Table F6 in Appendix F for detailed results.

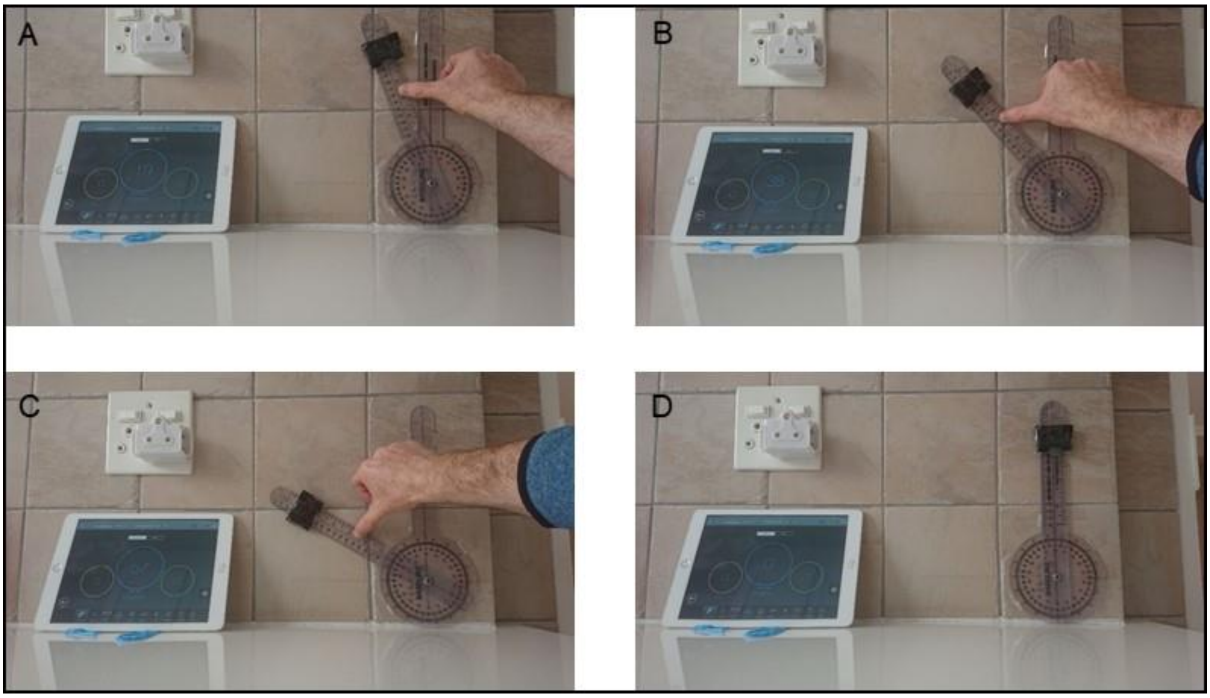

Fig. 4. 18 A) A 19º reading at the anti-clockwise 20º position. B) The application displays 38º at the 40º marker. C) A 57º reading at the anti-clockwise 60º position. D) The application displays 0º on return to the starting position.

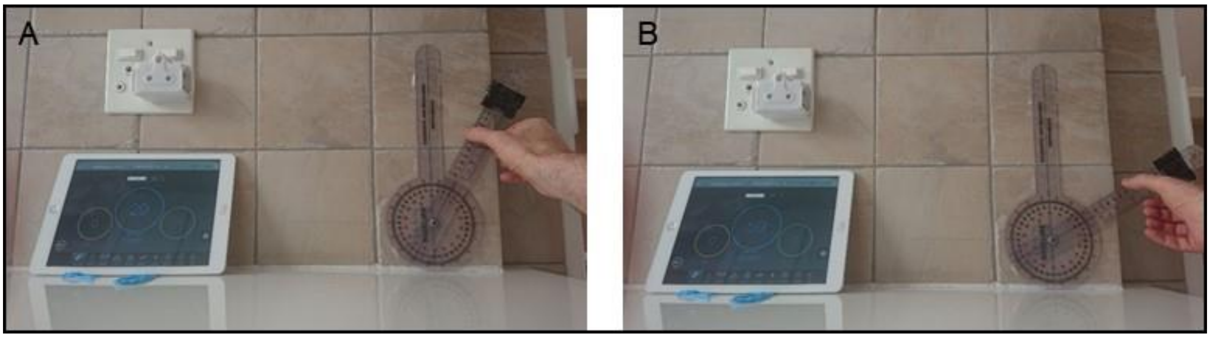

Fig. 4. 19 A) The application reads 29º at the clockwise 30º position. B) The tablet displays 59º at the clockwise 60º marker.

On a second spell of testing, the same result emerged. After recalibration, the sensor was moved anti-clockwise directly to the 40º point; there was still a 2º error, displaying a 38º reading. The author concluded that there was no gyroscope drift in the inverted position through the transverse plane, it appears though, that the sensor has improved performance when orientated upright. As noted before in the sagittal plane testing, although the arc of movement differed, once again the sensor's angle measurement function performed better in the upright than the inverted position. For this reason, the sensor was orientated in the upright position across the hip rotation testing positions to further angle measurement accuracy.

4.4.9 Validation Study 9

Aim: To Determine Whether the IMU's Angle Measurement Function Performed Accurately and Experienced Gyroscope Drift in the Transverse Plane Through the "n" Arc of Motion in the Upright Position

The sensor was tested in its upright position in the transverse plane, through the "n" arc of motion, to evaluate its angle measurement functionality and identify any gyroscope drift during hip rotation ROM measurement in the prone position. The IMU was taped to the mobile arm of the goniometer on its midpoint lines, right-side up in keeping with the orientation of the sensor in human testing. The flat side of the sensor was mounted on the mobile arm, to ensure that the ridges on the sensor's casing didn't affect the reading. The goniometer's stationary arm was then mounted perfectly vertical on a wall. The sensor was calibrated at the 0º mark (Fig. 4.20A) and the goniometer's mobile arm was then moved 10 times (5 times in each direction through the 0º mark) through to the 80º positions. Thereafter, it was returned to the starting point and moved in the anti-clockwise direction; readings were taken at each 10º increment. It displayed errors ranging from 0º to 2º. There was no discrepancy at the 10º and 20º points (Fig. 4.20B); 1º error at the 30º, 40º and 50º markers (Fig. 4.20C) and 2º faults thereafter (Fig. 4.20D). It was then returned to the starting point and without recalibration, was then moved in a clockwise direction to different positions. Again errors ranged from 0º to 2º. It concurred perfectly at the 10º point (Fig. 4.21A); was 1º amiss through the 20º to 40º positions (Fig. 4.21B) and then displayed a 2º error at the remaining points (Fig. 4.21C). On return to the starting position, it displayed a 0º reading (Fig. 4.21D). See Table F7 in Appendix F for detailed results.

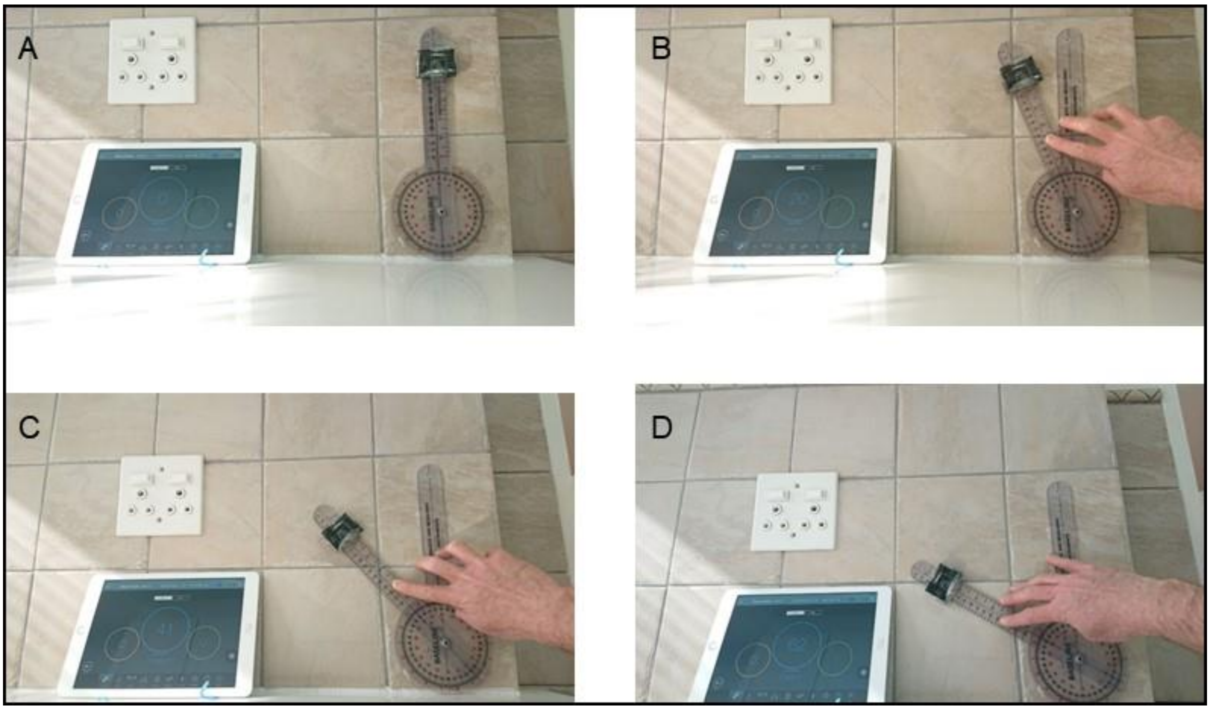

Fig. 4. 20 A) The application was calibrated at the start of the test. B) The application displays a 20º reading at the 20º anti-clockwise position. C) The tablet demonstrates a reading of 41º at the anti-clockwise 40º marker. D) The application shows a reading of 62º at the anti-clockwise 60º position.

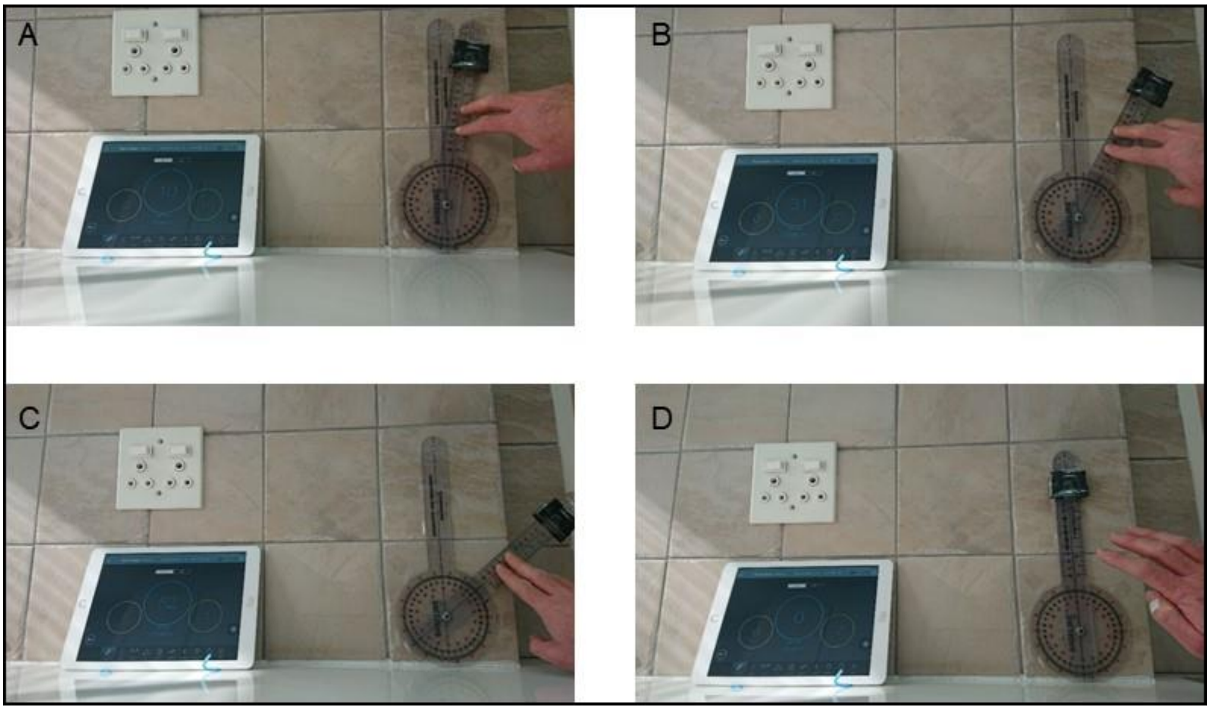

Fig. 4. 21 A) Both the application and goniometer concurrently demonstrate a 10º reading. B) The application displays a reading of 31º in the clockwise 30º position. C) A reading of 52º is displayed at the 50º clockwise marker. D) A 0º reading on return to the starting position.

These larger angles' two degree errors were of little concern, as hip rotation does not usually achieve these ranges and because the results fell in what was considered an "acceptable" reliability error range (Cuesta-Vargas et al., 2010). In conclusion, the IMU's angle measurement functionality proved accurate and displayed no gyroscope drift in the transverse plane, through the "n" arc of motion and when in the upright position.

4.4.10 Validation Study 10

Aim: To Determine Whether the IMU's Angle Measurement Function Performed Accurately and Experienced Gyroscope Drift in the 60º-to-Horizontal Plane through the "u" Arc of Motion in the Upright Position

As the sensor was to be used to measure angles in a plane 60º-to-horizontal plane, validation studies were necessary to test angle measurement functionality and determine any gyroscope drift in this position. Once again, a previously established square floor tile was propped, at a 60º angle, against a vertical wall while resting on a horizontal table. With the sensor's midpoints identified, it was mounted upright on the mobile arm of a goniometer and the stationary arm secured to the tile on a marked axis. The sensor's angle measurement function was calibrated at the 0º mark and then the goniometer's mobile arm was moved 10 times (5 times in each direction), through the 0º mark to the 80º positions. Thereafter, it was returned to the starting point and moved clockwise, where readings were taken at each 10º increment in the 0º to 80º range. There was never more than a 1º error at each mark (Fig. 4.22A). It was then returned to the starting point, where it registered a 1º fault (Fig. 4.22B). Without recalibrating, it was then moved anti-clockwise, again to the 10º, 20º, 30º, 40º, 50º, 60º, 70º and 80º positions. Here too, there was never more than a 1º error at each marker (Fig. 4.23A and Fig. 4.23B). On return to the starting position, it once again displayed a 1º discrepancy. See Table F8 in Appendix F for detailed results.

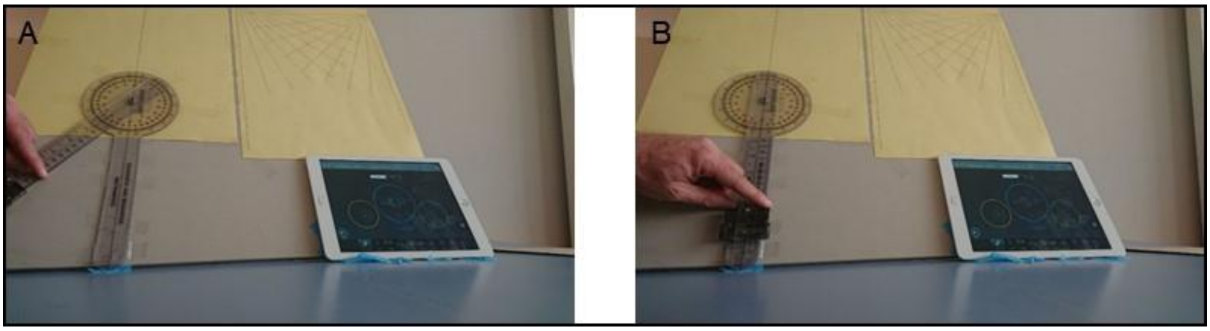

Fig. 4. 22 A) The tablet shows a reading of 41º at the 40º clockwise position. B) The application displays 1º on return to the 0º position.

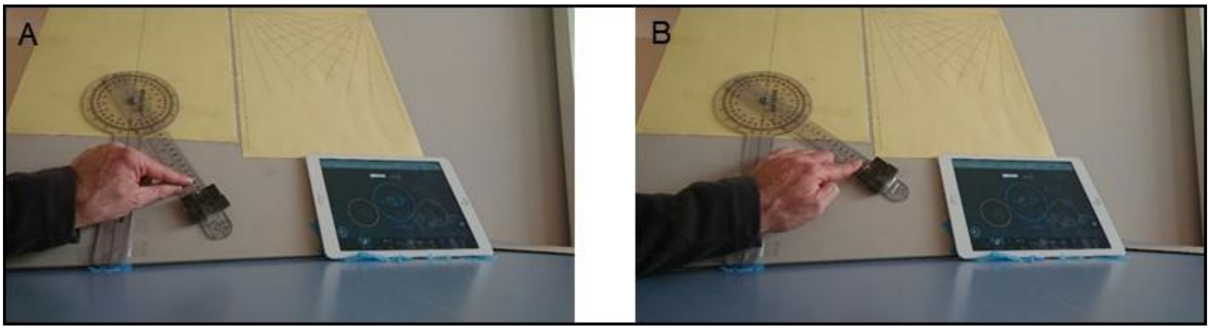

Fig. 4. 23 A) The application shows a 30º reading at the 30º anti-clockwise position. B) 51º displayed at the anti-clockwise 50º goniometer position.

This study proved that the IMU's angle measurement function was accurate and demonstrated no gyroscope drift in the plane 60º-to-the-horizontal through the "u" arc of motion in the upright position.

4.4.11 Validation Study 11

Aim: To Determine Whether the IMU's Spirit Level Angle Measurement Function Performed Accurately and Experienced Gyroscope Drift in the Transverse Plane, Comprising Two Different Arcs of Motion in the Vertical Plane, and in the 60º-to-Horizontal Plane

Finally, one of the studies' objectives required comparison of hip rotation range in three different positions of hip flexion. Literature review revealed previous methodology employed (Clarkson, 2013; Ellison et al., 1990; Van Dillen et al., 2008) in hip rotation measurement used plumb-line vertical as the starting reference point. This would be afforded by the IMU's spirit level. Already validated for determining the starting points, it also needed to provide consistent angle measurement functionality without gyroscope drift in a vertical (moving through two different arcs of movement) and 60º-to-horizontal plane.

This validation study consisted of three tests, each requiring the sensor be secured to a goniometer's mobile arm. As earlier angle measurement testing had shown the sensor was less reliable when inverted, the IMU was only assessed in the upright position in all three tests. Test one, consisted of a vertical goniometer's mobile arm, below its circular body, swinging through a "u" shaped arc (simulating sitting hip rotation assessment). Similarly, test two's goniometer was also positioned vertically, but inverted with the mobile arm above the body, the sensor passing through an "n" shaped arc (simulating prone hip rotation assessment). Lastly, test three's goniometer was placed at a 60^{o}-to-horizontal position, again with the mobile arm below the circular body, the sensor traversed a "u" shaped arc (simulating supine 30^{o} hip rotation assessment). The necessary spirit level's angle measurement functionality was thus evaluated in the following manner:

As before, a pencilled line was plotted 15cm from one of the floor tile's sides. The same tile with pencilled axis was to be used in the vertical, for tests one and two and placed at a 60^{o} pitch for test three. A bubble spirit level was used to ensure that the tile, resting on a table against a wall, was perfectly level in the horizontal and perfectly right in the vertical planes. The "flat" side of the sensor was secured to the goniometer's mobile arm and then the stationary arm mounted on the pencilled axis.

With each of the three tests, the IMU's spirit level was activated with the goniometer's mobile arm in the vertical, 0^{o} position - the mobile arm (and sensor) were then moved clockwise and anti-clockwise to the 90^{o} points respectively, moving through the 0^{o} point 10 times, 5 times to each side. Care was taken not to bump the sensor while the goniometer's mobile arm was moved through the range. The mobile arm was then moved to each 10^{o} point progressively from 10^{o} to 90^{o} in one direction, returned to the starting position and then moved to each 10^{o} point successively from 10^{o} to 90^{o} in the other direction, and then once again returned to the starting point.

In test one, the sensor displayed a 1^{o} reading at the start of the procedure. In the clockwise direction, the sensor displayed a 2^{o} error at each marker (Fig. 4.24A), with the exception of the 90° point where it was 3° adrift. In the anti-clockwise direction, it was between 0° and 2° amiss (Fig. 4.24B and Fig. 4.24C), once again it showed a 3° discrepancy at the 90° mark. On return to the vertical position, at the end of this test, it again presented a 1° reading (Fig. 4.24D). It also confirmed that the spirit-level functionality displayed no gyroscope drift when used in the vertical plane. See Table F9 in Appendix F for detailed results.

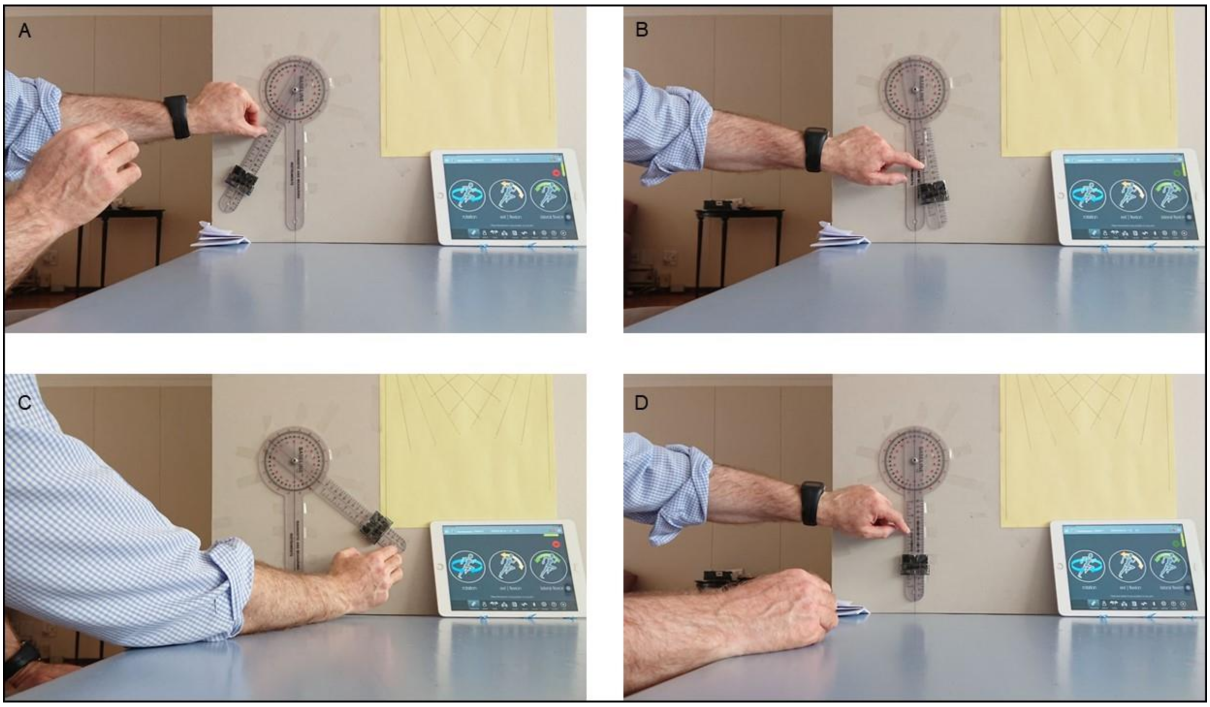

Fig. 4. 24 A) The spirit level function displays 32° at the goniometer's clockwise 30° position. B) The tablet demonstrates a reading of 8° at the 10° anti-clockwise position. C) The application reads 50° at the goniometer's anti-clockwise 50° position. D) A 1° reading on return to the start position.

In test two, the sensor perfectly corresponded with the goniometer in their vertical position, displaying a 0° reading at the start and end of the test. In the anti-clockwise direction, it demonstrated either a 0° or 1° error at each marker (Fig. 4.25A and Fig. 4.25B), with the exception of the 90° point where it was again 3° adrift. In the clockwise direction, it presented a 1° to 2° fault at each point (Fig. 4.25C and Fig. 4.25D); it displayed a 3° discrepancy at the 90° mark. See Table F10 in Appendix F for detailed results. Yet again, it confirmed that the spirit-level functionality displayed no gyroscope drift when used in the vertical plane travelling through this arc of motion.

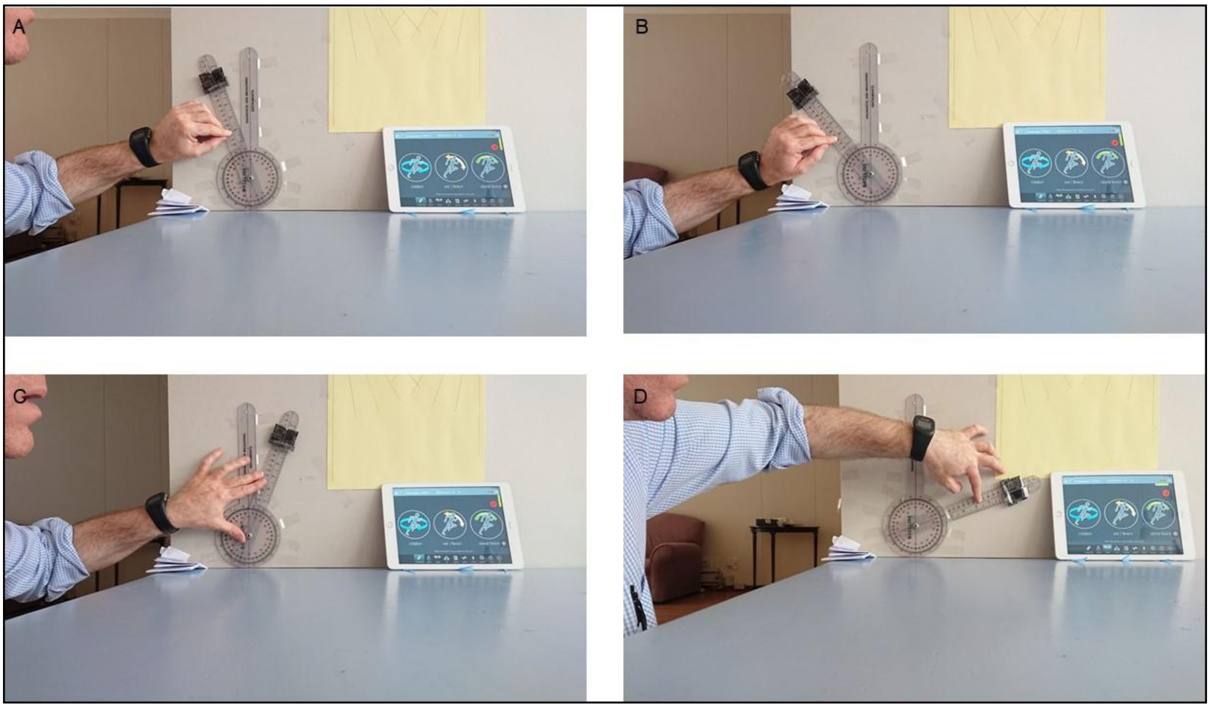

Fig. 4. 25 A) At the 20º anti-clockwise position, the application displayed a 19º reading. B) The application demonstrates a 40º reading at the 40º anti-clockwise marker. C) The tablet shows a reading of 21º in the 20º clockwise position. D) The application reads 72º in the 70º goniometric position.

In test three, when passing through a 60º-to-horizontal plane, the sensor's spirit level's angle measurement function performed inconsistently. The sensor displayed a 1º reading on activation and on return to the starting position at the end of the procedure. In the clockwise direction, there was a 0º, 1º and 2º discrepancy at the 10º (Fig. 4.26A), 20º and 30º (Fig. 4.26B) points respectively. Its performance deteriorated from there, being 4º, 6º, 10º, 14º, 20º and 29º amiss at 40º (Fig. 4.26C), 50º (Fig. 4.26D), 60º, 70º, 80º and 90º markers respectively. In the anti-clockwise direction the measurements were more unreliable. It was 3º, 4º, 5º, 7º, 9º, 12º, 15º, 21º and 30º out at the 10º (Fig. 4.27A), 20º (Fig. 4.27B), 30º (Fig. 4.27C), 40º (Fig. 4.27D), 50º, 60º, 70º, 80º and 90º points respectively. See Table F11 in Appendix F for detailed results. This third test was performed a second time and similar outcomes were obtained.

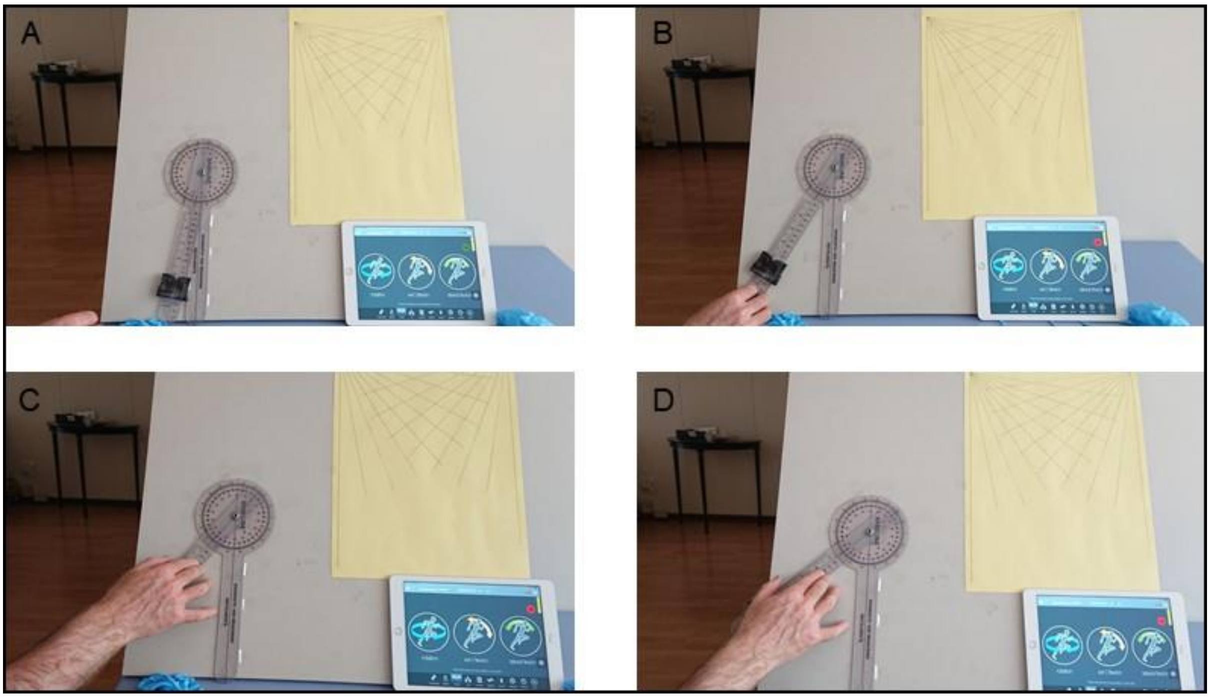

Fig. 4. 26 A) The application displays a 10º reading at the 10º clockwise marker. B) The tablet shows a reading of 28º in the 30º clockwise goniometric position. C) Thirty six degrees appears on the applications display at the goniometric 40º clockwise position. D) The application displays 44º at the 50º clockwise marker.

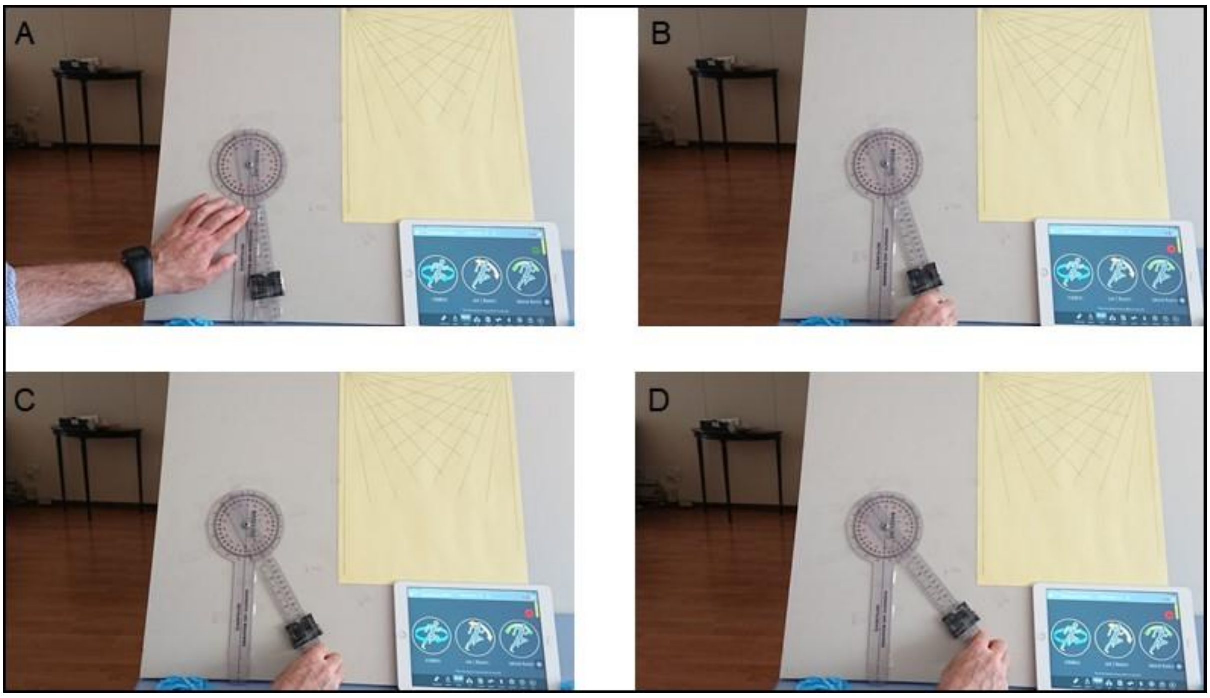

Fig. 4. 27 A) The application displays 7º at the 10º anti-clockwise point. B) The tablet demonstrates 16º at the 20º anti-clockwise marker. C) A 25º reading is visible at the goniometer's 30º anti-clockwise point. D) The application displays 33º at the goniometer's 40º anti-clockwise position.

In conclusion, when in the upright position but traversing through a 60º-to-horizontal plane, the sensor's spirit level function was accurate in determining when its lower border was horizontal. As set out above, the spirit level function may only be of use when measuring smaller angles in this plane. These inaccuracies made it impossible to conclude whether the spirit-level functionality experiences gyroscope drift in the 60º-to-horizontal plane.

Throughout the validation testing error of parallax was considered and negated at all times.

4.5 Validation Studies Summary

Table 4. 1 Summary of the Validation Study Results

Validation Test Objective	**Results**
Validation study 1: To determine the ability of the IMU's spirit level function to find horizontal in a vertical plane in its upright and inverted positions.	The IMU's spirit level accurately identified the perfect horizontal, and thereby vertical, in the upright and inverted positions, it displayed a 1^{o} error and 0^{o} reading respectively.
Validation study 2: To determine the ability of the IMU's spirit level function to find horizontal in a 60^{o}-to-horizontal plane.	The IMU's spirit-level perfectly identified horizontal when moving through a 60^{o}-to-horizontal plane; it displayed a 0^{o} reading when the bottom edge was horizontal.
Validation study 3: To determine whether the IMU's spirit level function's ability to find horizontal in a 60^{o}-to-horizontal plane, is affected by gyroscope drift.	The IMU's spirit-level displayed no gyroscope drift when moving through a 60^{o}-to-horizontal plane; it displayed a 0^{o} reading at the start and end of the test.
Validation study 4: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the frontal plane.	The IMU's angle measurement functionality was accurate but experienced notable gyroscope drift in the frontal plane testing. When moved once to a specific position in either clockwise or anti-clockwise direction, there was a 1^{o} error. Recalibration was therefore necessary for each movement.

Validation study 5: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the sagittal plane in the upright position.	The IMU's angle measurement functionality was accurate and experienced no gyroscope drift in the sagittal plane testing in the upright position. There was never more than a 1º error for all the acute and obtuse angles tested. It also found its starting position with a 1º error.
Validation study 6: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the sagittal plane in the inverted position.	The IMU's angle measurement functionality displayed greater inaccuracies but experienced no gyroscope drift in the sagittal plane testing in the inverted position. Depending on the chosen angle there were 1 to 3º inaccuracies, it also found its starting position with a 1º error.
Validation study 7: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the transverse plane through the "u" arc of motion in the upright position.	The IMU's angle measurement functionality displayed some inaccuracies but experienced no gyroscope drift in the transverse plane testing when in the upright position passing through a "u" arc of motion. In the 0º to 80º range, it displayed mostly 1º errors with a 2º fault at the 70º and 80º position in the anti-clockwise direction. It found its starting point with a 1º error.
Validation study 8: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope	The IMU's angle measurement functionality displayed greater inaccuracies but experienced no gyroscope drift in the transverse plane

drift in the transverse plane through the "n" arc of motion in the inverted position.	testing in the inverted position through an "n" arc of motion. Depending on the chosen angle there were 1^o to 3^o errors. However, it perfectly located the starting position.
Validation study 9: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the transverse plane through the "n" arc of motion in the upright position.	The IMU's angle measurement functionality displayed some inaccuracies but experienced no gyroscope drift in the transverse plane when in the upright position passing through an "n" arc of motion. Errors ranged from 0^o to 2^o, with 0^o and 1^o errors at smaller angles. On its return, it recognised the starting point perfectly.
Validation study 10: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the 60^o-to-horizontal plane through the "u" arc of motion in the upright position.	The IMU's angle measurement function was accurate and experienced no gyroscope drift in the 60^o-to-horizontal plane testing. It displayed a 1^o error at each marker in the 0^o to 80^o range in the clockwise and anti-clockwise direction. There was a 1^o error on return to the starting point.
Validation study 11: To determine whether the IMU's spirit level angle measurement function performed accurately and experienced gyroscope drift in the transverse plane, comprising two different arcs of motion, and in the 60^o-to-horizontal plane.	The IMU's spirit level angle measurement functionality was accurate and experienced no gyroscope drift in the transverse plane testing in both the "u" and "n" arcs of motion in the upright position. The "u" shaped arc displayed a 0^o to 2^o error at different markers and a

	3º error at the 90º positions, with a 1º disparity on return to the starting point. The "n" shaped arc again demonstrated a 0º to 2º error with a 3º error at the 90º positions. It confirmed the perfectly vertical position on return to the starting point. Although, there was a 1º discrepancy on return to the starting point, the IMU performed poorly in the 60º-to-horizontal plane testing making a verdict on gyroscope drift impossible. Traversing a "u" shaped arc it relayed a 5º error in the 30º anti-clockwise position, larger angles presented still greater errors.

When compared to other systems, this IMU performed relatively well with an error rate lower than what was observed in these other studies (Bolink et al., 2015; Zügner, et al., 2019; El-Gohary and McNames, 2015; Robert-Lachaine et al., 2017). A notable shortcoming occurs when inverted, this was simply countered by appropriately orientating the sensor during testing. The angle measurement functionality's accuracy also diminished slightly at 70º and 80º positions in the transverse plane testing. Since hip rotation does not achieve these ranges, it is unlikely that this limitation had any effect on the studies' results. Gyroscope drift was also predictably noticeable in the frontal plane measurements, this weakness was negated by recalibrating the sensor at the start of each abduction or adduction trial.

The greatest flaw identified, was the spirit level's angle measurement accuracy in the 60º-to-horizontal plane. To obtain greater precision, the IMU's spirit level and angle measurement functions were jointly exploited to compare hip rotation range in the three hip flexion positions - the spirit level to identify the starting position and angle measurement function to measure the range. This necessitated switching between functionalities and resulted in the IMU being recalibrated at the start of each rotation movement in all three hip flexion positions. In order to determine whether the IMU could be used to evaluate the differing hip flexion positions' impact on hip rotation ROM, a comparative analysis of the results from validation studies 7, 10 and 9 was performed (see Table F12 and F13 in Appendix F). This showed that through the eight different goniometric points, the sensor never differed more than 2^{o} (from the goniometer) across the three sagittal plane positions. It also indicated that the IMU was comparatively never more than 1^{o} amiss across its three sagittal plane excursions, in both the clockwise and anti-clockwise directions.

To conclude, the Shemesh Health Solutions IMU was found to be a valid device for use in the measurement of hip ROM as required for this study.

Chapter 5 Results

5.1 Descriptive statistics

The study's convenience sample consisted of 95 participants, 52 men and 43 women, ranging from 41 to 81 years of age (mean age 55.03 years ± 10.46) with a mean BMI of 25.0 ± 2.8 kg/m^2. The overall average Beighton Scale score was 2.31 ±1.85 and mean Baecke questionnaire results for work, sport, leisure and total indices was 2.39 (± 0.57), 3.07 (± 0.95), 2.79 (± 0.57) and 8.25 (± 1.53), respectively. Each group's characteristics are detailed in section 5.3 below.

The study's counts and expected counts appear in the Gender Table (Table 5.1 below). A Pearson Chi-Square p-value of 0.833 was calculated, indicating that there was no significant relationship between gender and lumbar pain status.

Table 5. 1 The Relationship Between Lumbar Pain and Gender

Gender	**Lumbar Pain Group n (%)**	**Control Group n (%)**	**Total N (%)**	**P-Value**
Male	34 (54%)	18 (56.25%)	52 (54.74%)	0.833
Female	29 (46%)	14 (43.75%	43 (45.26%)	

5.2 Hip ROM Analyses

In order to supplement the hip joint ROM literature, two hip range analyses were undertaken. For the first, the complete cohort's (n = 95) left and right sides were combined and utilised (n = 190) to obtain a value for each hip range variable. Consequently, the results comprised both genders. Every hip range variable's mean or median can be seen in Table 5.2 below depending on the results of their distribution analysis. This analysis was empowered by the fact that there were no significantly different findings between the group's hip range variables (see section 5.4 below). The quoted SLR results were MTT adjusted. The "Total Rotation" variables combine both side's hip internal and ER at each of the three saggital plane positions. For the second ROM value analysis, the complete cohort's (n = 95) left and right side's hip range variables are separately presented (n = 95) in Table 5.3 below. The mean and standard deviation is cited for normally distributed variables and median, interquartile range and range is quoted for variables with skewed data. Once again, the results comprise both genders and the quoted SLR results were MTT adjusted. Here the "Total Rotation" variables state each side's combined internal and ER ROM for each saggital plane position.

Table 5. 2 Hip ROM Values (n=190)

Variable	**Mean ROM (O)**	**Median ROM (O)**	**Standard Deviation (O)**	**Inter-quartile Range (O)**	**Range (O)**	**Shapiro-Wilk p-value**
MTT (Knee Extended)	-9.10		6.09			0.562
SLR*		71.00		59.50 - 83.33	104.67	0.012
Hip Flexion	129.63		9.35			0.655
Hip Extension	32.04		6.37			0.935
Hip Abduction*		44.33		40.25 - 48.67	41.67	0.031
Hip Adduction	28.67		5.11			0.451
Hip IR Supine 30^o	41.67		10.14			0.124
Hip ER Supine 30^o	59.85		8.86			0.785

Hip Total Rotation Supine 30^o	101.52		14.10			0.318
Hip IR Prone	41.62		10.20			0.128
Hip ER Prone	55.78		9.27			0.172
Hip Total Rotation Prone*		96.67		88.25 - 105.67	71.67	0.042
Hip IR Sitting	40.99		8.67			0.093
Hip ER Sitting	51.42		7.19			0.929
Hip Total Rotation Sitting	92.41		11.80			0.556

Key: * - denotes a variable with a skewed distribution.

Table 5. 3 Left and Right Side Hip ROM Values (n=95)

Variable	Mean ROM (^{O})	Median ROM (^{O})	Standard Deviation (^{O})	Inter-quartile Range (^{O})	Range (^{O})	Shapiro-Wilk p-value
MTT (Knee Extended) Left Hip	-9.00		6.10			0.402
MTT (Knee Extended) Right Hip	-9.19		6.10			0.993
SLR Left Hip*		73.00		60.00 - 87.67	92.67	0.025
SLR Right Hip	71.39		16.75			0.482

Hip Flexion Left	130.45		9.04			0.703
Hip Flexion Right	128.80		9.63			0.713
Hip Extension Left	32.78		6.88			0.928
Hip Extension Right	31.29		5.76			0.532
Hip Abduction Left	44.61		6.62			0.080
Hip Abduction Right*		45.00		40.33 - 48.67	41.67	0.041
Hip Adduction Left	29.66		5.37			0.812
Hip Adduction Right	27.67		4.67			0.496
Hip IR Supine 30^o Left	40.76		10.63			0.367
Hip ER Supine 30^o Left	62.15		7.86			0.501
Hip Total Rotation Supine 30^o Left	102.91		13.73			0.524
Hip IR Supine 30^o Right	42.58		9.60			0.129
Hip ER Supine 30^o Right	57.54		9.23			0.772
Hip Total Rotation Supine 30^o Right	100.12		14.39			0.537

Hip IR Prone Left	42.42		10.44			0.306
Hip ER Prone Left	57.15		9.37			0.443
Hip Total Rotation Prone Left	99.57		12.29			0.310
Hip IR Prone Right	40.82		9.95			0.080
Hip ER Prone Right	54.42		9.01			0.290
Hip Total Rotation Prone Right	95.24		11.65			0.117
Hip IR Sitting Left	42.97		9.18			0.466
Hip ER Sitting Left	51.05		7.02			0.704
Hip Total Rotation Sitting Left	94.02		11.74			0.091
Hip IR Sitting Right	39.00		7.67			0.220
Hip ER Sitting Right	51.79		7.37			0.407
Hip Total Rotation Sitting Right	90.79		11.70			0.795

Key: * - denotes a variable with a skewed distribution.

Table 5.4 below details the descriptive statistics of the lumbar pain (n=63) and control group's (n=32) variables. Age, BMI, Beighton score, Baecke indices and left and right side's hip range variables are listed. An asterisk denotes a variable with a skewed distribution. The MTT has negative mean and median scores, indicating the limb's end position below the horizontal. Analysis was performed on the MTT adjusted, SLR results. Once more, each side's internal and ER's measures were combined to report that side's "total rotation" - this was repeated for each sagittal plane position, namely, supine, prone and sitting.

Table 5. 4 Group's Variable's Descriptive Statistics

Variable	Lumbar Pain Group (n = 63)			Control Group (n = 32)		
	Mean ± SD	**Range**	**Median (Interquartile Range)**	**Mean ± SD**	**Range**	**Median (Interquartile Range)**
Age (y)*	54.33 ± 9.87*	40*	51 (46 - 61)*	56.41 ± 11.57*	34*	57.5 (46.25 - 67.75)*
BMI (kg/m^2)*	25.08 ± 2.71*	11.7*	25.40 (23.1 - 27.3)*	24.85 ± 3.15	12.40	25.00 (23.48 - 26.80)
Beighton Score*	2.30 ± 1.94*	7*	2 (0 - 4)*	2.31 ± 1.67*	7*	2 (1 - 3)*
Baecke Work Index*	2.35 ± 0.58*	2.63*	2.13 (2.00 - 2.63)*	2.48 ± 0.56	2.25	2.38 (2.13 - 2.84)
Baecke Sport Index*	2.91 ± 1.00*	3.5*	2.75 (2.00 - 3.75)*	3.39 ± 0.77	3.50	3.50 (2.81 - 4.00)
Baecke Leisure Index	2.69 ± 0.56	2.5	2.75 (2.25 – 3.00)	2.99 ± 0.53	2.5	3.00 (2.75 - 3.25)
Baecke Total Index*	7.95 ± 1.53	6.50	8.00 (6.75 - 9.13)	8.86 ± 1.35*	4.50*	9.00 (7.78 - 10.22)*

MTT (Knee Extended) Left Hip (º)	-9.26 ± 6.64	30.67	-9.67 (-13.67 - -5.00)	-8.49 ± 4.94	21	-8.67 (-12.25 - -5.75)
MTT (Knee Extended) Right Hip (º)	-9.99 ± 6.28	32	-10.67 (-14.00 - -5.67)	-7.60 ± 5.48	23.67	-7.33 (-11.67 - -4.42)
SLR Left Hip (º)*	76.09 ± 18.30*	87.67*	73.00 (60.00 - 90.67)*	72.83 ± 16.11	66.33	73.50 (60.83 - 81.67)
SLR Right Hip (º)	71.64 ± 17.75	76.33	68.00 (58.00 - 83.33)	70.91 ± 14.83	71.33	70.33 (63.00 - 80.83)
Hip Flexion Left (º)	130.50 ± 8.57	40	129.00 (125.33 - 137.33)	130.34 ± 10.04	41.67	129.33 (121.83 - 138.25)
Hip Flexion Right (º)	128.77 ± 9.83	50.33	127.67 (121.67 - 136.00)	128.88 ± 9.38	39.00	127.83 (120.92 - 137.17)
Hip Extension Left (º)	32.59 ± 7.72	37.67	31.67 (28.00 - 39.00)	33.17 ± 4.93	19.33	34.17 (30.17 - 37.17)
Hip Extension Right (º)	30.84 ± 6.22	26	30.00 (26.33 - 34.33)	32.18 ± 4.71	18.33	32.50 (28.08 - 36.25)

Hip Abduction Left (º)	44.30 ± 6.39	29.67	44.33 (39.33 - 47.33)	45.23 ± 7.12	26.67	43.50 (40.50 - 51.75)
Hip Abduction Right (º)*	44.76 ± 7.03*	41.67*	44.67 (40.33 - 48.67)*	45.30 ± 6.06	23.33	45.33 (39.75 - 49.33)
Hip Adduction Left (º)	29.39 ± 5.46	25.67	29.33 (25.67 – 33.00)	30.19 ± 5.22	21.67	30.83 (25.75 - 33.67)
Hip Adduction Right (º)	27.13 ± 4.87	23	26.67 (23.67 - 30.33)	28.75 ± 4.10	23.33	29.17 (26.33 - 30.33)
Hip IR Supine 30º Left (º)	41.14 ± 10.30	45	41.67 (33.00 - 48.33)	40.01 ± 11.37	43	39.67 (31.83 - 45.67)
Hip ER Supine 30º Left (º)*	61.89 ± 7.51	33.67	62.33 (56.67 - 66.33)	62.67±8.60*	36.67*	61.00 (57.58 - 66.33)*
Hip Total Rotation	103.03 ± 12.59	63	103.00 (93.33 - 113.33)	102.68 ± 15.94	57	102.33 (87.67 - 113.08)

Supine 30º Left (º)						
Hip IR Supine 30º Right (º)*	43.30 ± 9.82	45.33	44.00 (36.33 - 50.67)	41.18 ± 9.13*	32.33*	39.50 (33.83 - 46.58)*
Hip ER Supine 30º Right (º)	57.20 ± 9.16	41.67	57.00 (51.33 - 64.00)	58.21 ± 9.49	40.67	57.00 (51.00 - 64.67)
Hip Total Rotation Supine 30º Right (º)	100.49 ± 13.49	63.33	99.67 (90.00 - 112.00)	99.39 ± 16.22	71.33	98.00 (87.75 - 108.92)
Hip IR Prone Left (º)	43.16 ± 10.94	51.67	42.67 (37.00 - 51.67)	40.96 ± 9.37	38.33	39.83 (36.17 - 45.92)
Hip ER Prone Left (º)	56.84 ± 9.97	49	57.00 (50.00 - 62.33)	57.77 ± 8.17	28.67	57.83 (51.33 - 64.42)
Hip Total Rotation	100.00 ± 12.86	71.67	100.67 (92.33 - 108.67)	98.73 ± 11.26	44.67	97.50 (90.33 - 105.58)

Prone Left (º)						
Hip IR Prone Right (º)	41.07 ± 10.30	56.33	40.00 (34.00 - 48.33)	40.32 ± 9.37	37.67	38.83 (35.17 - 47.5)
Hip ER Prone Right (º)	54.93 ± 9.59	53.33	54.33 (48.67 – 61.00)	53.42 ± 7.77	30.33	55.00 (46.67 - 58.58)
Hip Total Rotation Prone Right (º)	96.00 ± 11.93	56.33	96.00 (85.67 - 104.33)	93.74 ± 11.10	46	94.67 (85.83 - 97.92)
Hip IR Sitting Left (º)	43.30 ± 9.11	41.67	44.00 (36.33 - 48.67)	42.32 ± 9.42	34	39.83 (35.83 - 49.58)
Hip ER Sitting Left (º)	51.10 ± 7.51	41	51.67 (46.33 - 54.67)	50.97 ± 6.05	24	51.17 (46.83 - 55.58)
Hip Total Rotation	94.39 ± 12.11	56	95.00 (84.67 - 103.00)	93.29 ± 11.12	42.33	91.50 (86.42 – 103.00)

Sitting Left (º)						
Hip IR Sitting Right (º)	38.67 ± 7.60	34.33	38.33 (34.00 – 43.00)	39.66 ± 7.89	29	38.67 (33.25 - 44.92)
Hip ER Sitting Right (º)	51.87 ± 7.43	31	52.00 (46.33 - 57.33)	51.64 ± 7.35	27.33	50.67 (44.42 - 57.83)
Hip Total Rotation Sitting Right (º)	90.54 ± 11.26	59	91.67 (83.00 - 97.67)	91.29 ± 12.68	50	90.17 (82.58 - 98.92)

Key: * - denotes a variable with a skewed distribution.

5.3 Variable Distribution Analyses

Each group's left and right variables' Shapiro-Wilk distribution analyses' results appear in Table 5.5 below. An asterisk denotes a variable with a skewed distribution.

Table 5. 5 Group's Variable's Normality Test Results

Variable	Pain Group Shapiro-Wilk p-value	Control Group Shapiro-Wilk p-value
Age *	0.002*	0.011*
BMI *	0.018*	0.092
Beighton Scale *	<0.001*	0.011*
Baecke Work Index *	0.008*	0.078
Baecke Sport Index *	0.017*	0.289
Baecke Leisure Index	0.221	0.419
Baecke Total Index*	0.509	0.036*
MTT (Knee Extended) Left Hip	0.540	0.329
MTT (Knee Extended) Right Hip	0.895	0.996
SLR Left Hip*	0.010*	0.988
SLR Right Hip	0.109	0.711
Hip Flexion Left	0.973	0.794
Hip Flexion Right	0.739	0.485
Hip Extension Left	0.807	0.057
Hip Extension Right	0.373	0.579
Hip Abduction Left	0.319	0.149
Hip Abduction Right*	0.037*	0.369
Hip Adduction Left	0.814	0.913
Hip Adduction Right	0.605	0.062
Hip IR Supine 30^o Left	0.749	0.421
Hip ER Supine 30^o Left*	0.857	0.031*
Hip Total Rotation Supine 30^o Left	0.864	0.222

Hip IR Supine 30º Right*	0.645	0.019*
Hip ER Supine 30º Right	0.966	0.075
Hip Total Rotation Supine 30º Right	0.528	0.159
Hip IR Prone Left	0.490	0.302
Hip ER Prone Left	0.411	0.235
Hip Total Rotation Prone Left	0.191	0.694
Hip IR Prone Right	0.232	0.192
Hip ER Prone Right	0.438	0.235
Hip Total Rotation Prone Right	0.294	0.404
Hip IR Sitting Left	0.631	0.180
Hip ER Sitting Left	0.769	0.750
Hip Total Rotation Sitting Left	0.270	0.139
Hip IR Sitting Right	0.537	0.404
Hip ER Sitting Right	0.665	0.276
Hip Total Rotation Sitting Right	0.766	0.652

Key: * - denotes a variable with a skewed distribution.

5.4 Results of Objective 1 and 2 Statistical Analyses

Determination and Comparison of the Lumbar Pain and Control Group's Hip ROM

No significant difference was found between the two group in terms of age, BMI and Beighton scores. Although the group's work activity was the same, a statistically significant difference was found between their sport, leisure and total indices. A small effect was evident for the sport and total indices, while there was a medium effect between groups in the leisure index. No significant difference was found between the groups for any of the hip ROM variables. The results appear in Table 5.6 below.

Table 5. 6 Comparison of the Group's Characteristics and Passive Hip ROM

Variable	Lumbar Pain Group	Control Group	Cohen's d Effect Size	Levene's Equality of Variances test (p-value)	t	df	Two-tailed p-value. Asymp. Sig. (2-talied)	95% CI
Age(y)** Median(IQR)	51 (46 -61)**	57.5 (46.25 - 67.75)**	.071				0.488	
BMI(kg/m^2)** Median(IQR)	25.40 (23.1 - 27.3)**	25.00 (23.48 - 26.80)	.040				0.697	
Beighton Scale** Median(IQR)	2 (0 - 4)**	2 (1 - 3)**	.020				0.843	
Baecke Work Index** Median(IQR)	2.13 (2.00 - 2.63)**	2.38 (2.13 - 2.84)	.123				0.230	
Baecke Sport Index** Median(IQR)	2.75 (2.00 - 3.75)**	3.50 (2.81 - 4.00)	.223				0.029	
Baecke Leisure Index* Mean ± SD; SEM	2.69±0.56; 0.07	2.99±0.53;0.09	.553	0.477	-2.547	93	0.013	-0.54 - -0.07
Baecke Total Index** Median(IQR)	8.00 (6.75 - 9.13)	9.00 (7.78 - 10.22)**	.276				0.007	

MTT (Knee Extended) Left Hip(º)* Mean±SD; SEM	-9.26± 6.64; 0.84	-8.49± 4.94; 0.87	.126	0.048	-.579	93	0.564	-3.41 - 1.87
MTT (Knee Extended) Right Hip(º)* Mean±SD; SEM	-9.99± 6.28; 0.79	-7.60± 5.48; 0.97	.397	0.463	-1.827	93	0.071	-4.99 - 0.21
SLR Left Hip(º)** Median(IQR)	73.00 (60.00 - 90.67)**	73.50 (60.83 - 81.67)	.060				0.557	
SLR Right Hip(º)* Mean±SD; SEM	71.64±17.75; 2.24	70.91±14.83; 2.62	.044	0.095	.201	93	0.841	-6.52 - 7.99
Hip Flexion Left(º)* Mean±SD; SEM	130.50±8.57; 1.08	130.34±10.04; 1.77	.017	0.213	.081	93	0.936	-3.76 - 4.08
Hip Flexion Right(º)* Mean±SD; SEM	128.77±9.83; 1.24	128.88±9.38; 1.66	.011	0.808	-.051	93	0.959	-4.28 - 4.07
Hip Extension Left(º)* Mean±SD; SEM	32.59±7.72; 0.97	33.17±4.93; 0.87	.084	0.011	-.386	93	0.700	-3.56 - 2.40

Hip Extension Right(º)* Mean±SD; SEM	30.84±6.22; 0.78	32.18±4.71; 0.83	.232	0.163	-1.069	93	0.288	-3.82 - 1.15
Hip Abduction Left(º)* Mean±SD; SEM	44.30±6.39; 0.81	45.23±7.12; 1.26	.140	0.254	-.643	93	0.522	-3.79 - 1.94
Hip Abduction Right(º)** Median(IQR)	44.67 (40.33 - 48.67)**	45.33 (39.75 - 49.33)	.044				0.665	
Hip Adduction Left(º)* Mean±SD; SEM	29.39±5.46; 0.69	30.19±5.22; 0.92	.149	0.988	-.685	93	0.495	-3.12 - 1.52
Hip Adduction Right(º)* Mean±SD; SEM	27.13±4.87; 0.61	28.75±4.10; 0.72	.351	0.147	-1.616	93	0.109	-3.62 - 0.37
Hip IR Supine 30º Left(º)* Mean±SD; SEM	41.14±10.30; 1.30	40.01±11.37; 2.01	.106	0.497	.487	93	0.628	-3.47 - 5.73
Hip ER Supine 30º Left(º)** Median(IQR)	62.33 (56.67 - 66.33)	61.00 (57.58 - 66.33)**	.015				0.887	
Hip Total Rotation Supine 30º Left(º)*	103.03±12.59; 1.59	102.68±15.94; 2.82	.026	0.069	.118	93	0.906	-5.59 - 6.30

Mean±SD; SEM									
Hip IR Supine 30º Right(º)** Median(IQR)	44.00 (36.33 - 50.67)		39.50 (33.83 - 46.58)**	.124			93	0.227	
Hip ER Supine 30º Right(º)* Mean±SD; SEM	57.20±9.16;	1.15	58.21±9.49; 1.68	.109	0.958	-.503	93	0.616	-5.01 - 2.98
Hip Total Rotation Supine 30º Right(º)* Mean±SD; SEM	100.49±13.49; 1.70		99.39±16.22; 2.87	.077	0.506	.353	93	0.725	-5.13 - 7.34
Hip IR Prone Left(º)* Mean±SD; SEM	43.16±10.94;	1.38	40.96±9.37; 1.66	.211	0.353	.973	93	0.333	-2.30 - 6.71
Hip ER Prone Left(º)* Mean±SD; SEM	56.84±9.97;	1.26	57.77±8.17; 1.44	.099	0.559	-.458	93	0.648	-4.99 - 3.12
Hip Total Rotation Prone Left(º)* Mean±SD; SEM	100±12.86;	1.62	98.73±11.26; 1.99	.103	0.533	.474	93	0.636	-4.05 - 6.59
Hip IR Prone Right(º)* Mean±SD; SEM	41.07±10.30;	1.30	40.32±9.37; 1.66	.075	0.553	.346	93	0.730	-3.56 - 5.06

Hip ER Prone Right(º)* Mean±SD; SEM	54.93±9.59; 1.21	53.42±7.77; 1.37	.167	0.335	.770	93	0.443	-2.38 - 5.40
Hip Total Rotation Prone Right(º)* Mean±SD; SEM	96.00±11.93; 1.50	93.74±11.10; 1.96	.194	0.505	.893	93	0.374	-2.77 - 7.29
Hip IR Sitting Left(º)* Mean±SD; SEM	43.30±9.11; 1.15	42.32±9.42; 1.66	.106	0.600	.487	93	0.628	-3.00 - 4.95
Hip ER Sitting Left(º)* Mean±SD; SEM	51.10±7.51; 0.95	50.97±6.05; 1.07	.018	0.351	.083	93	0.934	-2.92 - 3.17
Hip Total Rotation Sitting Left(º)* Mean±SD; SEM	94.39±12.11; 1.53	93.29±11.12; 1.97	.093	0.489	.430	93	0.668	-3.98 - 6.18
Hip IR Sitting Right(º)* Mean±SD; SEM	38.67±7.60; 0.96	39.66±7.89; 1.40	.128	0.587	-.589	93	0.557	-4.30 - 2.33
Hip ER Sitting Right(º)* Mean±SD; SEM	51.87±7.43; 0.94	51.64±7.35; 1.30	.031	0.930	.145	93	0.885	-2.96 - 3.42
Hip Total Rotation Sitting Right(º)*	90.54±11.26; 1.42	91.29±12.68; 2.24	.064	0.388	-.295	93	0.769	-5.82 - 4.32

Mean±SD; SEM									

Key: CG – Control Group; CI – Confidence Interval; df – degree of freedom; IQR – Interquartile Range; PG – Pain Group; SD – Standard Deviation; SEM - Standard Error of the Mean; *- denotes normal distribution, presented as mean, SD, SEM and analysed with the two-tailed independent t-test; **- denotes skewed distribution, presented as median, IQR and analysed with the Mann-Whitney U Test.

5.5 Results of Objective 3 Statistical Analyses

Comparison of the Pain and Control Group's Side-to-Side Hip Ranges' ROM

Although both group's variables displayed significant side-to-side differences, a greater number of hip ranges were identified in the pain group. In the pain group, a significant side-to-side difference was seen in SLR; flexion; extension; adduction; IR supine 30º; ER supine 30º; total rotation supine 30º; IR prone; total rotation prone; IR sitting and total rotation sitting ranges. Effect sizes varied greatly. Refer to Table 5.7 below for details.

Significant side-to-side differences were seen in the control group's ER supine 30º; total rotation supine 30º; ER prone; total rotation prone and IR sitting ranges. Medium to large effect sizes were mostly observed. Detailed results appear in Table 5.8 below.

Table 5. 7 Comparison of the Lumbar Pain Group's Side-to-Side Hip ROM

Variables	Lumbar Pain Group Left Hip ROM	Lumbar Pain Group Right Hip ROM	Cohen's d Effect Size	t	Two-tailed p-value Asymp. Sig. (2-tailed)	95% CI
MTT (Knee Extended)(°)* Mean ± SD	-9.26 ± 6.64	-9.99 ± 6.28	.222	1.762	0.083	-0.10 - 1.57
SLR(°)** Median(IQR)	73.00 (60.00 - 90.67)	68.00 (58.00 - 83.33)	.597		<0.001	
Hip Flexion(°)* Mean ± SD	130.50 ± 8.57	128.77 ± 9.83	.350	2.780	0.007	0.49 - 2.98
Hip Extension(°)* Mean ± SD	32.59 ± 7.72	30.84 ± 6.22	.365	2.894	0.005	0.54 - 2.95
Hip Abduction(°)** Median(IQR)	44.33 (39.33 - 47.33)	44.67 (40.33 - 48.67)	.068		0.592	
Hip Adduction(°)* Mean ± SD	29.39 ± 5.46	27.13 ± 4.87	.488	3.875	<0.001	1.09 - 3.42
Hip IR Supine 30° (°)*	41.14 ± 10.30	43.30 ± 9.82	.270	2.143	0.036	-4.17 - -0.14

Mean ± SD						
Hip ER Supine 30º (º)* Mean ± SD	61.89 ± 7.51	57.20 ± 9.16	.630	5.000	<0.001	2.82 - 6.58
Hip Total Rotation Supine 30º (º)* Mean ± SD	103.03 ± 12.59	100.49 ± 13.49	.295	2.339	0.023	0.37 - 4.71
Hip IR Prone(º)* Mean ± SD	43.16 ± 10.94	41.07 ± 10.30	.280	2.224	0.03	0.21 - 3.97
Hip ER Prone(º)* Mean ± SD	56.84 ± 9.97	54.93 ± 9.59	.244	1.934	0.058	-0.06 - 3.88
Hip Total Rotation Prone(º)* Mean ± SD	100.00 ± 12.86	96.00 ± 11.93	.568	4.505	<0.001	2.23 - 5.77
Hip IR Sitting(º)* Mean ± SD	43.30 ± 9.11	38.67 ± 7.60	.697	5.536	<0.001	2.95 - 6.29
Hip ER Sitting(º)*	51.10 ± 7.51	51.87 ± 7.43	.130	-1.034	0.305	-2.27 - 0.72

Mean ± SD						
Hip Total Rotation Sitting(º)* Mean ± SD	94.39 ± 12.11	90.54 ± 11.26	.637	5.057	<0.001	2.33 - 5.37

Key: CI – Confidence Interval; SD – Standard Deviation; * - denotes normal distribution, presented as mean, SD and analysed with the Paired samples t-test; ** - denotes skewed distribution, presented as median, IQR and analysed with the Wilcoxon Signed Rank Test.

Table 5. 8 Comparison of the Control Group's Side-to-Side Hip ROM

Variable	Control Group Left Hip ROM	Control Group Right Hip ROM	Cohen's d Effect Size	t	Two-tailed p-value Asymp. Sig. (2-tailed)	95% CI
MTT (Knee Extended)(º)* Mean ± SD	-8.49 ± 4.94	-7.60 ± 5.48	.229	-1.297	0.204	-2.28 - 0.51
SLR(º)* Mean ± SD	72.83 ± 16.11	70.91 ± 14.83	.279	1.577	0.125	-0.56 - 4.42
Hip Flexion(º)* Mean ± SD	130.34 ± 10.04	128.88 ± 9.38	.279	1.581	0.124	-0.43 - 3.36
Hip Extension(º)* Mean ± SD	33.17 ± 4.93	32.18 ± 4.71	.278	1.572	0.126	-0.29 - 2.27
Hip Abduction(º)* Mean ± SD	45.23 ± 7.12	45.30 ± 6.06	.016	-0.089	0.93	-1.75 - 1.60
Hip Adduction(º)* Mean ± SD	30.19 ± 5.22	28.75 ± 4.10	.293	1.658	0.107	-0.33 - 3.21

Hip IR Supine 30º (º)** Median(IQR)	39.67 (31.83 - 45.67)	39.50(33.83 - 46.58)**	.139**		0.432**	
Hip ER Supine 30º (º)** Median(IQR)	61.00 (57.58 - 66.33)**	57.00 (51.00 - 64.67)	.542**		0.002**	
Hip Total Rotation Supine 30º (º)* Mean ± SD	102.68 ± 15.94	99.39 ± 16.22	.462	2.613	0.014	0.72 - 5.86
Hip IR Prone(º)* Mean ± SD	40.96 ± 9.37	40.32 ± 9.37	.095	0.536	0.596	-1.78 - 3.05
Hip ER Prone(º)* Mean ± SD	57.77 ± 8.17	53.42 ± 7.77	.593	3.354	0.002	1.71 - 7.00
Hip Total Rotation Prone(º)* Mean ± SD	98.73 ± 11.26	93.74 ± 11.10	.823	4.653	<0.001	2.80 - 7.18
Hip IR Sitting(º)* Mean ± SD	42.32 ± 9.42	39.66 ± 7.89	.387	2.189	0.036	0.18 - 5.15
Hip ER Sitting(º)*	50.97 ± 6.05	51.64 ± 7.35	.108	-0.609	0.547	-2.90 - 1.57

Mean ± SD						
Hip Total Rotation Sitting(º)* Mean ± SD	93.29 ± 11.12	91.29 ± 12.68	.264	1.492	0.146	-0.73 - 4.73

Key: CI – Confidence Interval; SD – Standard Deviation; * - denotes normal distribution, presented as mean, SD and analysed with the Paired samples t-test; ** - denotes skewed distribution, presented as median, IQR and analysed with the Wilcoxon Signed Rank Test.

5.6 Results of Objective 4 and 5 Statistical Analyses

To Determine Whether There is an Association Between Hypomobile and Hypermobile Hip Ranges and their Coupled Symptomatic Lumbar Ranges

As outlined in section 3.8.3 above, participants were sorted into the control subgroup, symptomatic lumbar range pain subgroup or asymptomatic lumbar range pain subgroup depending on whether the relevant lumbar range was symptomatic. Each subgroup's associated hip ROM was then compared. These subgroup pairwise comparison's results appear in Table 5.10 to Table 5.19 below. If a control subgroup's participant presented with a symptomatic lumbar range, they remained in the (control subgroup's) analysis because of the study's robust exclusionary process and their declared pain-free status. These cases are however highlighted in each section's preamble.

Each subgroup's lumbar range's coupled hip ROM's means were tested for normality and the results thereof appear in Table 5.9 below. Where small subgroup sample sizes precluded normality testing, "not applicable" appears in the table. Consequently, non-parametric testing was used for these variable's analyses. When a hip ROM feature (eg. hip anteversion) presented in none and/or one of a subgroup's participants, normality testing and any other statistical analyses was rendered impossible. In this event, "not analysed" appears in Table 5.9 below.

Table 5. 9 Normality Analysis of the Subgroup's Lumbar Range's Coupled Hip ROM

Variable	Control Subgroup -Hip Range Shapiro-Wilk p-value	Symptomatic Lumbar Pain Subgroup - Hip Range Shapiro-Wilk p-value	Asymptomatic Lumbar Pain Subgroup - Hip Range Shapiro-Wilk p-value
Lumbar Flexion - SLR Means Analysed	0.984	0.129	0.076
Lumbar Flexion – Hip Flexion/Squat Medians Analysed	Not Applicable	Not Applicable	Not Applicable
Lumbar Extension - Hip Extension Means Analysed	0.656	0.920	0.650
Lumbar Extension - Iliopsoas Length Means Analysed	0.424	0.695	0.865
Left Lumbar Lateral Flexion – Right Hip Adduction Means Analysed	0.062	0.481	0.356
Right Lumbar Lateral Flexion – Left Hip Adduction Means Analysed	0.912	0.428	0.875
Left Lumbar Rotation– Left Hip IR = Right Hip ER Medians Analysed	Not Applicable	Not Applicable	Not Applicable

Left Lumbar Rotation– Left Hip IR< Right Hip ER Medians Analysed	Not Applicable	Not Applicable	Not Applicable
Left Lumbar Rotation– Left Hip IR>Right Hip ER	Not Analysed	Not Analysed	Not Analysed
Right Lumbar Rotation– Right Hip IR = Left Hip ER Medians Analysed	Not Applicable	Not Applicable	Not Applicable
Right Lumbar Rotation– Right Hip IR, Left Hip ER (IR<ER) Medians Analysed	Not Applicable	Not Applicable	Not Applicable
Right Lumbar Rotation– Right Hip IR, Left Hip ER (IR>ER)	Not Analysed	Not Analysed	Not Analysed

5.6.1 Lumbar Flexion and SLR Coupling –Comparison of the Means of the Subgroup's Averaged Left and Right SLR ROM

Thirty two control subgroup participants were used in this analysis, 32 symptomatic subgroup participants had symptoms with lumbar flexion, while 31 pain subgroup participants were asymptomatic. One control subgroup participant experienced lower back pain with bending. No significant difference was found between any of the subgroup's averaged SLR ROM. The symptomatic lumbar flexion pain subgroup exhibited the lowest mean range, followed by the control subgroup with the asymptomatic lumbar flexion pain subgroup showing the greatest range. See Table 5.10 below.

Table 5. 10 Lumbar Flexion and SLR Coupling – Pairwise Comparisons of the Means of the Subgroup's Averaged Left and Right SLR ROM

Subgroup* Number of Subgroup Participants** Variable (I): Mean (±SD) of Averaged Left and Right SLR ROM(º)***	Subgroup* Number of Subgroup Participants** Variable (J): Mean (±SD) of Averaged Left and Right SLR ROM(º)***	Mean Difference (Variable I-J)■ (95% CI)■■	Std. Error	Sig. p-value
Symptomatic Lumbar Flexion Pain Subgroup* 32** 70.11º(±16.42) ***	Asymptomatic Lumbar Flexion Pain Subgroup* 31** 77.74º (±18.30) ***	-7.632■ (-17.823 - 2.558)■■	4.193	0.200
Symptomatic Lumbar Flexion Pain Subgroup* 32** 70.11º(±16.42) ***	Lumbar Flexion Control Subgroup* 32** 71.87º (±15.09)***	-1.760■ (-11.870 - 8.350)■■	4.160	0.965
Lumbar Flexion Control Subgroup* 32** 71.87º (±15.09)***	Asymptomatic Lumbar Flexion Pain Subgroup* 31** 77.74º (±18.30) ***	-5.872■ (-16.063 - 4.319)■■	4.193	0.415

Key: * - Subgroup being compared; ** - Number of participants in the Subgroup; *** - Hip variable's ROM in degrees; ■ – Mean difference between the subgroup's variables; ■■ – 95% confidence interval; SD – Standard Deviation

5.6.2 Lumbar Flexion and Hip Flexion/Squat Coupling – Comparison of the Medians of the Subgroup's Averaged Left and Right Hip Flexion ROM

Again, 32 control subgroup participants' results were utilised in this analysis. Only nine participants in the symptomatic lower back pain subgroup presented with lumbar pain during the squat test, the remaining 54 lumbar pain participants were asymptomatic. None of the control subgroup's volunteers experienced lower back pain with squatting. There was no significant difference in median hip flexion (squatting) range across the three subgroups; $H(2) = 0.83$, $p = 0.661$. The post hoc subgroup pairwise comparisons are presented in Table 5.11 below. The null hypothesis was therefore retained.

Table 5. 11 Lumbar Flexion and Hip Flexion/Squat Coupling – Pairwise Comparisons of the Medians of the Subgroup's Averaged Left and Right Hip Flexion ROM

Subgroup* Number of Subgroup Participants Median(IQR) of Averaged Left and Right Hip Flexion ROM(º)*****	**Subgroup* Number of Subgroup Participants** Median(IQR) of Averaged Left and Right Hip Flexion ROM(º)*****	**Std. Error**	**Sig. p-value**
Symptomatic Lumbar Squat Pain Subgroup* 9** 133º (124.67 - 139.34)***	Asymptomatic Lumbar Squat Pain Subgroup* 54** 128.59º (123.55 - 134.83)***	9.925	0.365
Symptomatic Lumbar Squat Pain Subgroup* 9** 133º (124.67 - 139.34)***	Lumbar Squat Control Subgroup* 32** 129.25º (121.75 - 136.29)***	10.401	0.486
Lumbar Squat Control Subgroup* 32** 129.25º (121.75 - 136.29)***	Asymptomatic Lumbar Squat Pain Subgroup* 54** 128.59º (123.55 - 134.83)***	6.150	0.775

Key: * - Subgroup being compared; ** - Number of participants in the Subgroup; *** - Hip variable's ROM in degrees.

5.6.3 Lumbar Extension and Hip Extension Coupling – Comparison of the Means of the Subgroup’s Averaged Left and Right Hip Extension ROM

The control subgroup, asymptomatic lumbar extension pain subgroup and symptomatic lumbar extension pain subgroup consisted of 32, 28 and 35 participants respectively. Two of the control subgroup participants complained of lumbar extension pain on testing. There was no significant difference found between the three subgroup’s hip extension means. For details see Table 5.12 below.

Table 5. 12 Lumbar Extension and Hip Extension Coupling – Pairwise Comparisons of the Means of the Subgroup's Averaged Left and Right Hip Extension ROM

Subgroup* **Number of Subgroup Participants**** **Variable (I): Mean(±SD) of Averaged Left and Right Hip Extension ROM(°)*****	**Subgroup*** **Number of Subgroup Participants**** **Variable (J): Mean(±SD) of Averaged Left and Right Hip Extension ROM(°)*****	**Mean Difference (Variable I-J)■** **(95% CI)■■**	**Std. Error**	**Sig. p-value**
Symptomatic Lumbar Extension Pain Subgroup* 35** 30.76° (±6.00)***	Asymptomatic Lumbar Extension Pain Subgroup* 28** 32.91° (±7.18) ***	-2.155■ (-5.811 - 1.501)■■	1.504	0.395
Symptomatic Lumbar Extension Pain Subgroup* 35** 30.76° (±6.00)***	Lumbar Extension Control Subgroup* 32** 32.67° (±4.48)***	-1.915■ (-5.442 - 1.612)■■	1.451	0.466
Lumbar Extension Control Subgroup* 32** 32.67° (±4.48)***	Asymptomatic Lumbar Extension Pain* Subgroup 28** 32.91° (±7.18)***	-0.240■ (-3.971 - 3.492)■■	1.535	0.998

Key: * - Subgroup being compared; ** - Number of participants in the Subgroup; *** - Hip variable's ROM in degrees; ■ – Mean difference between the subgroup's variables; ■■ – 95% confidence interval; SD – Standard Deviation

5.6.4 Lumbar Extension and MTT Coupling – Comparison of the Means of the Subgroup's Averaged Left and Right Iliopsoas ROM

As lumbar extension was the MTT's coupled range, the same subgroup sample sizes were used here as those used for lumbar extension-hip extension's analysis above. As mentioned before, two control subgroup participants with symptomatic lumbar extension were used in this analysis. When comparing individual's with and without symptoms on lumbar extension, a significant difference was found between the symptomatic and asymptomatic subgroup and the control and asymptomatic subgroup's iliopsoas length (see Table 5.13 below).

Table 5. 13 Lumbar Extension and MTT Coupling – Pairwise Comparisons of the Means of the Subgroup's Averaged Left and Right Iliopsoas ROM

Subgroup* Number of Subgroup Participants** Variable (I): Mean (±SD) of Averaged Left and Right Iliopsoas ROM(º)***	Subgroup* Number of Subgroup Participants** Variable (J): Mean (±SD) of Averaged Left and Right Iliopsoas ROM(º)***	Mean Difference (Variable I-J)■ (95% CI)■■	Std. Error	Sig. p-value
Symptomatic Lumbar Extension Pain Subgroup* 35** -7.79º (±5.87) ***	Asymptomatic Lumbar Extension Pain Subgroup* 28** -11.93º (±6.02)***	4.143■ (0.695 - 7.590)■■	1.418	0.013
Symptomatic Lumbar Extension Pain Subgroup* 35** -7.79º (±5.87) ***	Lumbar Extension Control Subgroup* 32** -8.05º (±4.84)***	0.261■ (-3.065 - 3.586)■■	1.368	0.997
Lumbar Extension Control Subgroup* 32** -8.05º (±4.84)***	Asymptomatic Lumbar Extension Pain Subgroup* 28** -11.93º (±6.02)***	3.882■ (0.363 - 7.400)■■	1.448	0.026

Key: * - Subgroup being compared; ** - Number of participants in the Subgroup; *** - Hip variable's ROM in degrees; ■ – Mean difference between the subgroup's variables; ■■ – 95% confidence interval; SD – Standard Deviation

5.6.5 Lumbar Left Lateral Flexion and Right Hip Adduction Coupling - Comparison of the Means of the Subgroup's Right Hip Adduction ROM

As the left and right hips move in parallel during left lumbar lateral flexion and because adduction has a smaller range than abduction, it was assumed to be the controlling hip range. Therefore right hip adduction was analysed for left lateral flexion and vice versa. The control subgroup had 32 participants, the symptomatic lower back pain subgroup 29 and asymptomatic lower back pain subgroup 34 volunteers. None of the control subgroup experienced any lumbar symptoms with left lateral flexion. Levene's test result was $F(2, 92) = 3.66$, $p = 0.030$. As the assumption of homogeneity was not met, Welch's test was employed in the analysis and showed no significance between the subgroups $F(2, 61.00) = 2.11$, $p = 0.131$. Games Howell post hoc analysis was employed in the pairwise comparisons below. These details are quoted in Table 5.14.

Table 5. 14 Lumbar Left Lateral Flexion and Right Hip Adduction Coupling - Pairwise Comparisons of the Means of the Subgroup's Right Hip Adduction ROM

Subgroup* Number of Subgroup Participants** Variable (I): Mean (±SD) of Right Hip Adduction ROM(°)***	Subgroup* Number of Subgroup Participants** Variable (J): Mean (±SD) of Right Hip Adduction ROM(°)***	Mean Difference (Variable I-J)■ (95% CI)■■	Std. Error	Sig. p-value
Symptomatic Left Lateral Flexion Pain Subgroup* 29** 26.63° (±3.94)***	Asymptomatic Left Lateral Flexion Pain Subgroup* 34** 27.55° (±5.57)***	-0.918■ (-3.809 - 1.973)■■	1.202	0.727
Symptomatic Left Lateral Flexion Pain Subgroup* 29** 26.63° (±3.94)***	Left Lateral Flexion Control Subgroup* 32** 28.75° (±4.10)***	-2.118■ (-4.592 - 0.356)■■	1.029	0.108
Left Lateral Flexion Control Subgroup* 32** 28.75° (±4.10)***	Asymptomatic Left Lateral Flexion Pain Subgroup* 34** 27.55° (±5.57)***	1.200■ (-1.680 - 4.079)■■	1.198	0.579

Key: * - Subgroup being compared; ** - Number of participants in the Subgroup; *** - Hip variable's ROM in degrees; ■ – Mean difference between the subgroup's variables; ■■ – 95% confidence interval; SD – Standard Deviation

5.6.6 Lumbar Right Lateral Flexion and Left Hip Adduction Coupling - Comparison of the Means of the Subgroup's Left Hip Adduction ROM

The control subgroup consisted of 32 volunteers, the symptomatic lower back pain subgroup comprised 34 participants and the asymptomatic lower back pain subgroup, 29 people. Two control subgroup participants experienced lumbar pain with right lateral flexion. Here as with left lateral flexion, no significant difference was found between the subgroup's potentially limiting left hip adduction ROM. Please see Table 5.15 below.

Table 5. 15 Lumbar Right Lateral Flexion and Left Hip Adduction Coupling - Pairwise Comparisons of the Means of the Subgroup's Left Hip Adduction ROM

Subgroup* Number of Subgroup Participants** Variable (I): Mean (±SD) of Left Hip Adduction ROM(°)***	Subgroup* Number of Subgroup Participants** Variable (J): Mean (±SD) of Left Hip Adduction ROM(°)***	Mean Difference (Variable I-J) ■ (95% CI)■■	Std. Error	Sig. p-value
Symptomatic Right Lateral Flexion Pain Subgroup* 34** 29.32° (±5.45)***	Asymptomatic Right Lateral Flexion Pain Subgroup* 29** 29.46° (±5.58)***	-0.137■ (-3.462 - 3.189)■■	1.368	0.999
Symptomatic Right Lateral Flexion Pain Subgroup* 34** 29.32° (±5.45)***	Right Lateral Flexion Control Subgroup* 32** 30.19° (±5.22)***	-0.864■ (-4.104 - 2.376)■■	1.333	0.887
Right Lateral Flexion Control Subgroup* 32** 30.19° (±5.22)***	Asymptomatic Right Lateral Flexion Pain Subgroup* 29** 29.46° (±5.58)***	0.727■ (-2.646 - 4.100)■■	1.388	0.936

Key: * - Subgroup being compared; ** - Number of participants in the Subgroup; *** - Hip variable's ROM in degrees; ■ – Mean difference between the subgroup's variables; ■■ – 95% confidence interval; SD – Standard Deviation

5.6.7 Lumbar Left Rotation and Left Hip IR and Right Hip ER Coupling (Left Hip IR ROM = Right Hip ER ROM) - Comparison of the Medians of the Subgroup's Averaged Left Hip IR and Right Hip ER ROM

The control subgroup consisted of 13 volunteers, the symptomatic lower back pain subgroup included seven participants and the asymptomatic lower back pain subgroup, 17 people. None of the control subgroup participants with equal left internal and right external hip rotation experienced lumbar pain with left rotation. Comparing the average of the subgroup's left hip IR and right hip ER ranges, where the difference between the two hip ranges was less than or equal to 10^{o}, showed no significant difference between the left lumbar rotation subgroups; $H(2) = 0.311$, $p = 0.856$. For greater detail, the post hoc pairwise comparisons appear in Table 5.16 below.

Table 5. 16 Lumbar Left Rotation and Left Hip IR and Right Hip ER Coupling (Left Hip IR ROM = Right Hip ER ROM) - Pairwise Comparisons of the Medians of the Subgroup's Averaged Left Hip IR and Right Hip ER ROM

Subgroup* Number of Subgroup Participants** Median(IQR) of Averaged Left Hip IR ROM and Right Hip ER ROM(º)***	Subgroup* Number of Subgroup Participants** Median(IQR) of Averaged Left Hip IR ROM and Right Hip ER ROM(º)***	Std. Error	Sig. p-value
Symptomatic Left Lumbar Rotation Pain Subgroup* 7** 49.33º (44.33 – 52)***	Asymptomatic Left Lumbar Rotation Pain Subgroup* 17** 50º (45.67 - 53.83)***	4.859	0.737
Symptomatic Left Lumbar Rotation Pain Subgroup* 7** 49.33º (44.33 – 52)***	Left Lumbar Rotation Control Subgroup* 13** 47.33º (41.25 - 55.83)***	5.072	0.921
Left Lumbar Rotation Control Subgroup* 13** 47.33º (41.25 - 55.83)***	Asymptomatic Left Lumbar Rotation Pain Subgroup* 17** 50º (45.67 - 53.83)***	3.986	0.592

Key: * - Subgroup being compared; ** - Number of participants in the Subgroup; *** - Hip variable's ROM in degrees.

5.6.8 Lumbar Left Rotation and Left Hip IR Coupling (Left Hip IR ROM < Right Hip ER ROM) – Comparison of the Medians of the Subgroup's Left Hip IR ROM

The control subgroup consisted of 18 participants, the symptomatic lower back pain subgroup numbered three and the asymptomatic lower back pain subgroup had 32 volunteers. One control subgroup participant complained of pain with left lumbar rotation. No significant difference was found between the three subgroups' left lumbar rotation limiting, left hip IR range (right hip ER was 10º or more, than left hip IR); $H(2) = 1.849$, $p = 0.397$. The null hypothesis was retained. For greater detail, the post hoc pairwise comparisons appear in Table 5.17 below.

5.6.9 Lumbar Left Rotation and Right Hip ER Coupling (Right Hip ER ROM < Left Hip IR ROM)

It was not possible to perform an analysis of whether right hip ER range differed across the left lumbar rotation subgroups. Only one member of the control subgroup had right hip ER limiting, left lumbar rotation. Here right hip ER was 16º less than the participant's left hip IR. Four members of the asymptomatic lower back pain subgroup had relatively less right hip ER and none of the symptomatic lower back pain subgroup's participants demonstrated anteverted hips. As a result, the sample sizes prevented any such analysis.

Table 5. 17 Lumbar Left Rotation and Left Hip IR Coupling (Left Hip IR ROM < Right Hip ER ROM) - Pairwise Comparisons of the Medians of the Subgroup's Left Hip IR ROM

Subgroup* **Number of Subgroup Participants**** **Median(IQR) of Left Hip IR ROM(º)*****	**Subgroup*** **Number of Subgroup Participants**** **Median(IQR) of Left Hip IR ROM (º)*****	**Std. Error**	**Sig. p-value**
Symptomatic Left Lumbar Rotation Pain Subgroup* 3** 40º (39.00 - -)***	Asymptomatic Left Lumbar Rotation Pain Subgroup* 32** 38º (27.42 - 42.92)***	9.318	0.277
Symptomatic Left Lumbar Rotation Pain Subgroup* 3** 40º (39.00 - -)***	Left Lumbar Rotation Control Subgroup* 18** 37.33º (33.42 - 40.00)***	9.624	0.180
Left Lumbar Rotation Control Subgroup* 18** 37.33º (33.42 - 40.00)***	Asymptomatic Left Lumbar Rotation Pain Subgroup* 32** 38º (27.42 - 42.92)***	4.547	0.539

Key: * - Subgroup being compared; ** - Number of participants in the Subgroup; *** - Hip variable's ROM in degrees.

5.6.10 Lumbar Right Rotation and Right Hip IR and Left Hip ER Coupling (Right Hip IR ROM = Left Hip ER ROM) – Comparison of the Medians of the Subgroup's Averaged Right Hip IR and Left Hip ER ROM

The control and symptomatic lower back pain subgroups consisted of five volunteers each, while the asymptomatic lower back pain subgroup had 12 participants. None of the control subgroup members with equal right hip IR and left hip ER range experienced pain with right lumbar rotation. As before, there was no significant difference found between the medians of these three subgroups' right hip IR and left hip ER averages when performing right lumbar rotation; $H(2) = 0.159$, $p = 0.924$. The post hoc analysis of the three pairs appears in Table 5.18 below.

Table 5. 18 Lumbar Right Rotation and Right Hip IR and Left Hip ER Coupling (Right Hip IR ROM = Left Hip ER ROM) - Pairwise Comparisons of the Medians of the Subgroup's Averaged Right Hip IR and Left Hip ER ROM

Subgroup* Number of Subgroup Participants Median(IQR) of Averaged Right Hip IR ROM and Left Hip ER ROM(º)*****	**Subgroup* Number of Subgroup Participants** Median(IQR) of Averaged Right Hip IR ROM and Left Hip ER ROM(º)*****	**Std. Error**	**Sig. p-value**
Symptomatic Right Lumbar Rotation Pain Subgroup* 5** 51.67º (46 - 53.34)***	Asymptomatic Right Lumbar Rotation Pain Subgroup* 12** 49.25º (42.50 - 53.42)***	3.455	0.772
Symptomatic Right Lumbar Rotation Pain Subgroup* 5** 51.67º (46 - 53.34)***	Right Lumbar Rotation Control Subgroup* 5** 49.83º (43.75 - 57.33)***	4.105	0.961
Right Lumbar Rotation Control Subgroup* 5** 49.83º (43.75 - 57.33)***	Asymptomatic Right Lumbar Rotation Pain Subgroup* 12** 49.25º (42.50 - 53.42)***	3.455	0.728

Key: * - Subgroup being compared; ** - Number of participants in the Subgroup; *** - Hip variable's ROM in degrees.

5.6.11 Lumbar Right Rotation and Right Hip IR Coupling (Right Hip IR ROM < Left Hip ER ROM) - Comparison of the Medians of the Subgroup's Right Hip IR ROM

The control subgroup consisted of 26 volunteers, the symptomatic subgroup had 14 individuals and the asymptomatic subgroup 29 people. None of the control subgroup experienced pain with right lumbar rotation. On performing right lumbar rotation, no significant difference was found between the subgroup's right hip IR limiting range; $H(2) = 1.879$, $p = 0.391$. For further post hoc subgroup pairwise comparisons, please see Table 5.19 below.

5.6.12 Lumbar Right Rotation and Left Hip ER Coupling (Left Hip ER ROM < Right Hip IR ROM)

As before, small sample sizes prevented the analysis of whether relatively diminished left hip ER limiting, right lumbar rotation was different between the subgroups. Only one control group participant and three asymptomatic subgroup volunteers, presented with this biomechanical feature. None of the participants with symptomatic right lumbar rotation had anteverted hips.

Table 5. 19 Lumbar Right Rotation and Right Hip IR Coupling (Right Hip IR ROM < Left Hip ER ROM) - Pairwise Comparisons of the Medians of the Subgroup's Right Hip IR ROM

Subgroup* Number of Subgroup Participants** Median(IQR) of Right Hip IR ROM(º) ***	Subgroup* Number of Subgroup Participants** Median(IQR) of Right Hip IR ROM(º) ***	Std. Error	Sig. p-value
Symptomatic Right Lumbar Rotation Pain Subgroup* 14** 36.67º (34.83 - 43.17)***	Asymptomatic Right Lumbar Rotation Pain Subgroup* 29** 35º (31.50 - 42.17)***	6.527	0.225
Symptomatic Right Lumbar Rotation Pain Subgroup* 14** 36.67º (34.83 - 43.17)***	Right Lumbar Rotation Control Subgroup* 26** 37.33º (33.83 - 40.08)***	6.649	0.745
Right Lumbar Rotation Control Subgroup* 26** 37.33º (33.83 - 40.08)***	Asymptomatic Right Lumbar Rotation Pain Subgroup* 29** 35º (31.50 - 42.17)***	5.417	0.288

Key: * - Subgroup being compared; ** - Number of participants in the Subgroup; *** - Hip variable's ROM in degrees.

5.7 Results of Objective 6 and 7 Statistical Analyses

To Determine Whether Differing Sagittal Plane Positions Affect Hip Rotation ROM

The analysis of the hip rotation's side and position variables' Shapiro-Wilk results appear in Table 5.20 below. They were all found to be normally distributed.

Table 5. 20 Normality Analysis of the Different Sagittal Plane Positions' Hip Rotation Variables

Variable	Combined Sample Shapiro-Wilk Significance (n = 95)
Hip IR Prone Left	0.306
Hip IR Supine 30^o Left	0.367
Hip IR Sitting Left	0.466
Hip ER Prone Left	0.443
Hip ER Supine 30^o Left	0.501
Hip ER Sitting Left	0.704
Hip IR Prone Right	0.080
Hip IR Supine 30^o Right	0.129
Hip IR Sitting Right	0.220
Hip ER Prone Right	0.290
Hip ER Supine 30^o Right	0.772
Hip ER Sitting Right	0.407

5.7.1 The Effects of Sagittal Plane Positioning on Left Hip IR ROM

With Mauchly's assumption of sphericity having been met, χ^2 (2) = 0.282, p = 0.868, the spericity assumed, within-subjects effects' results were F(2,188) = 6.09, p = 0.003, ηp^2 = .06. The results of the one-way ANOVA showed that for left hip IR range, sagittal positioning did have a significant effect. Namely, the supine 30º hip flexion position, significantly reduced left hip IR ROM when compared to both the prone and sitting positions. There was no significant difference between the prone and sitting position's left hip IR range. See Fig. 5.1 and Table 5.21 below.

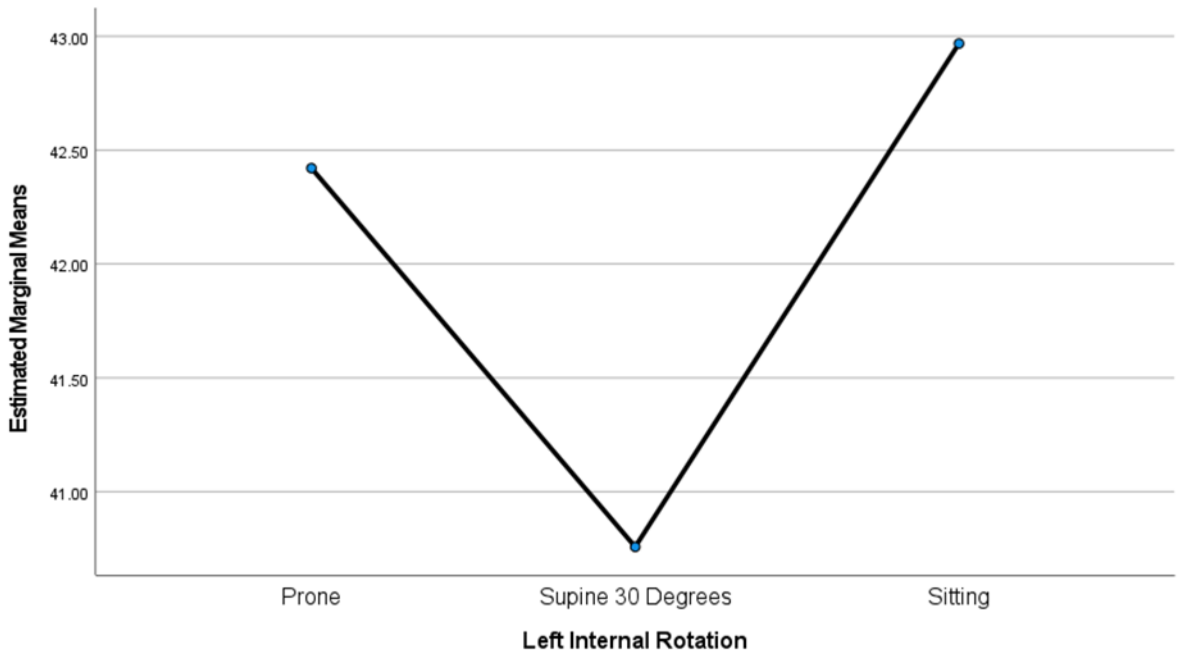

Fig. 5. 1 Sagittal Plane Positional Effects on the Mean of Left Hip IR ROM

Table 5. 21 Pairwise Comparisons of the Effects of Sagittal Plane Position on Left Hip IR ROM

Variable (I)* Mean (±SD) (º)**	Variable (J)* Mean (±SD) (º)**	Mean Difference (Variable I-J)■ (95% CI)■■	Std. Error	Sig. p-value
Hip IR Prone Left* 42.42º (±10.44)**	Hip IR Supine 30º Left* 40.76º (±10.63)**	1.663■ (0.026 - 3.301)■■	.672	0.045
Hip IR Prone Left* 42.42º (±10.44)**	Hip IR Sitting Left* 42.97º (±9.18)**	-0.55■ (-2.168 - 1.073)■■	.665	1.000
Hip IR Supine 30º Left* 40.76º (±10.63)**	Hip IR Sitting Left* 42.97º (±9.18)**	-2.211■ (-3.775 - -0.646)■■	.642	0.003

Key: * - Variable being compared; ** - The variable's ROM in degrees; ■ – Mean difference between the compared variables

■■ – 95% confidence interval; SD – Standard Deviation

5.7.2 The Effects of Sagittal Plane Positioning on Left Hip ER ROM

Left hip ER sagittal plane position's statistical analysis found significance for the pairs in Mauchly's Test of Sphericity, χ^2 (2) = 16.56, p = <0.001. Consequently, Greenhouse-Geisser analysis of within-subjects effects was utilised, with findings F(1.72,161.64) = 108.71, p = <0.001, ηp^2 = .54. Pairwise comparisons revealed a significantly different left hip ER range between each of the three sagittal plane positions, although the supine 30º measurement's mean was the greatest. Details appear in Fig. 5.2 and Table 5.22 below.

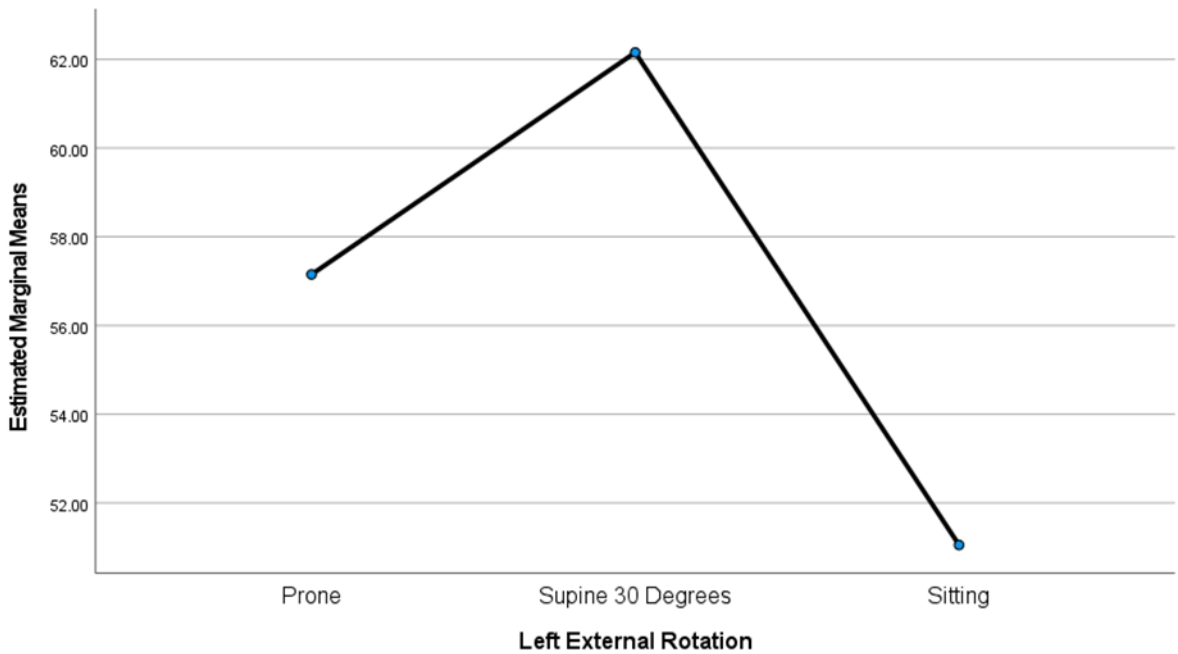

Fig. 5. 2 Sagittal Plane Positional Effects on the Mean of Left Hip ER ROM

Table 5. 22 Pairwise Comparisons of the Effects of Sagittal Plane Position on Left Hip ER ROM

Variable (I)* Mean (±SD) (º)**	Variable (J)* Mean (±SD) (º)**	Mean Difference (I-J)■ (95% CI)■■	Std. Error	Sig. p-value
Hip ER Prone Left* 57.15º (±9.37)**	Hip ER Supine 30º Left* 62.15º (±7.86)**	-5.004■ (-7.093 - -2.914)■■	0.857	<0.001
Hip ER Prone Left* 57.15º (±9.37)**	Hip ER Sitting Left* 51.05º (±7.02)**	6.098■ (4.174 - 8.023)■■	0.79	<0.001
Hip ER Supine 30º Left* 62.15º (±7.86)**	Hip ER Sitting Left* 51.05º (±7.02)**	11.10■ (9.663 - 12.540)■■	0.59	<0.001

Key: * - Variable being compared; ** - The variable's ROM in degrees; ■ – Mean difference between the compared variables

■■ – 95% confidence interval; SD – Standard Deviation

5.7.3 The Effects of Sagittal Plane Positioning on Right Hip IR ROM

Analysis of right hip IR sagittal plane position ROM's Mauchly's Test of Sphericity result was found to be insignificant, namely χ^2 (2) = 4.25, p = 0.12. The spericity assumed, within-subjects effects' results were F(2, 188) = 14.41, p = <0.001, ηp^2 = .13. The pairwise comparisons showed a marginally insignificant difference in right IR range between the prone and supine positions (p-value = 0.05, rounded down from 0.053); the result was deemed insignificant because the 95% CI crossed zero. A significant difference was seen in the right IR range between the prone and sitting and supine and sitting positions. The details appear in Fig. 5.3 and Table 5.23 below.

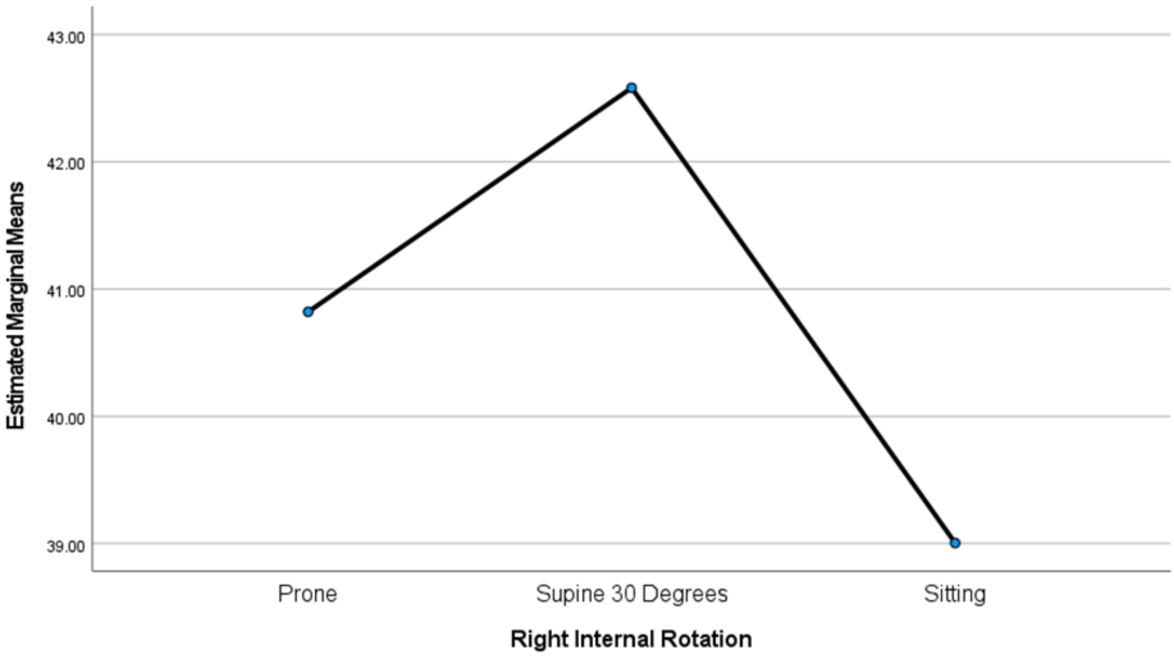

Fig. 5. 3 Sagittal Plane Positional Effects on the Mean of Right Hip IR ROM

Table 5. 23 Pairwise Comparisons of the Effects of Sagittal Plane Position on Right Hip IR ROM

Variable (I)* Mean (±SD) (º) **	Variable (J)* Mean (±SD) (º) **	Mean Difference (Variable I-J)■ (95% CI)■■	Std. Error	Sig. p-value
Hip IR Prone Right* 40.82º (±9.95)**	Hip IR Supine 30º Right* 42.58º (±9.60)**	-1.76■ (-3.540 - 0.018)■■	0.73	0.053
Hip IR Prone Right* 40.82º (±9.95)**	Hip IR Sitting Right* 39.00º (±7.67)**	1.82■ (0.330 - 3.305)■■	0.61	0.011
Hip IR Supine 30º Right* 42.58º (±9.60)**	Hip IR Sitting Right* 39.00º (±7.67)**	3.58■ (1.984 - 5.174)■■	0.65	<0.001

Key: * - Variable being compared; ** - The variable's ROM in degrees; ■ – Mean difference between the compared variables

■■ – 95% confidence interval; SD – Standard Deviation

5.7.4 The Effects of Sagittal Plane Positioning on Right Hip External Rotation ROM

Here, as before, the right hip ER sagittal plane position statistical analysis found significance for the pairs in Mauchly's Test of Sphericity, χ^2 (2) = 18.23, p = <0.001. Once again, Greenhouse-Geisser analysis of within-subjects effects was utilised, with findings of F(1.70, 159.60) = 20.99, p = <0.001, ηp^2 = .18. Pairwise comparisons revealed a significant difference in right hip ER range between each of the three sagittal plane positions, details of which appear in Fig. 5.4 and Table 5.24 below.

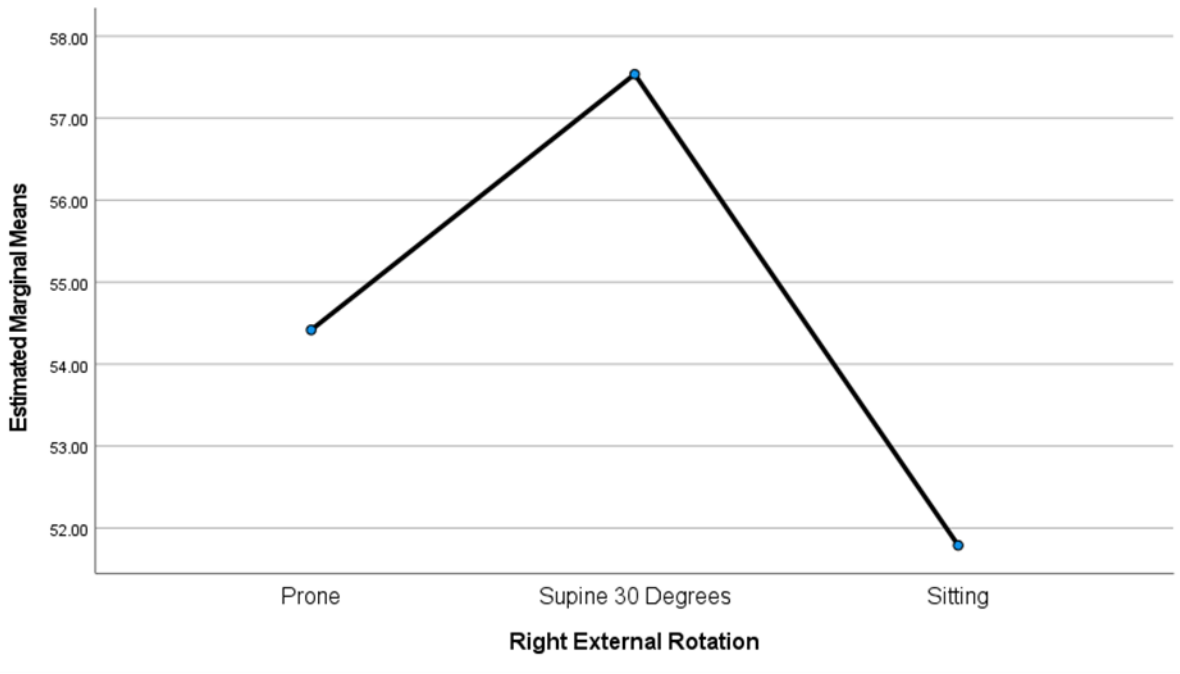

Fig. 5. 4 Sagittal Plane Positional Effects on the Mean of Right Hip ER ROM

Table 5. 24 Pairwise Comparisons of the Effects of Sagittal Plane Position on Right Hip ER ROM

Variable (I)* Mean (±SD) (º)**	Variable (J)* Mean (±SD) (º)**	Mean Difference (Variable I-J)■ (95% CI)■■	Std. Error	Sig. p-value
Hip ER Prone Right* 54.42º (±9.01)**	Hip ER Supine 30º Right* 57.54º (±9.23)**	-3.12■ (-5.657 - -0.582)■■	1.041	0.010
Hip ER Prone Right* 54.42º (±9.01)**	Hip ER Sitting Right* 51.79º (±7.37)**	2.63■ (0.482 - 4.774)■■	0.88	0.011
Hip ER Supine 30º Right* 57.54º (±9.23)**	Hip ER Sitting Right* 51.79º (±7.37)**	5.75■ (4.010 - 7.484)■■	0.71	<0.001

Key: * - Variable being compared; ** - The variable's ROM in degrees; ■ – Mean difference between the compared variables

■■ – 95% confidence interval; SD – Standard Deviation

5.8 Reliability Testing Results

The average Cronbach's Alpha score for the 30 variables that were analysed, was .900; with range .032 to .982. The author was unable to adequately explain why right hip abduction (with an outlier ICC of 0.032) scored so poorly. Left hip adduction, whose movement is in the same plane and direction, scored .927; it therefore stands to reason that the sensor could not be at fault. Similarly, other transverse plane movements, where gyroscope drift may have been most pronounced, such as left hip abduction and right hip adduction, scored "excellently" with alphas of .929 and .932 respectively. Despite this poor reliability rating, the 10 participant's test-retest, right hip abduction's mean and median results were 44.1 and 44.47 and 44 and 44.67 respectively. Furthermore, no statistically significant side-to-side hip abduction difference was found in either group, but it could also be argued that the low right hip abduction reliability could be responsible for overlooking a research result feature.

The only other ICC result with a score below .8, namely right hip ER in prone with a score of .778, could be explained by the knee movement's effects on the shin sited sensor. A difference of 20^{o} was noted between this ranges' test and retest averages in the first reliability participant. Thereafter a knee brace was introduced to fix the knee at 90^{o} for the prone rotation testing in all of the remaining participants. This one reliability and four earlier main study volunteers were the study's only unbraced participants. The reliability study results appear in Table 5.25 below.

Table 5. 25 Test-Retest Reliability Study Results

Variable	Cronbach's alpha	95% Confidence interval
MTT (Knee Extended) Left Hip	.954	.830 - .990
MTT (Knee Extended) Right Hip	.922	.711 - .982
SLR Left Hip	.969	.880 - .992
SLR Right Hip	.958	.846 - .990

Hip Flexion Left	.840	.394 - .962
Hip Flexion Right	.908	.544 - .972
Hip Extension Left	.911	.242 - .968
Hip Extension Right	.935	.723 - .982
Hip Abduction Left	.929	.736 - .984
Hip Abduction Right	.032	-4.656 -.778
Hip Adduction Left	.927	.732 - .983
Hip Adduction Right	.932	.751 - .984
Hip IR Supine 30º Left	.860	.442 - .962
Hip ER Supine 30º Left	.950	.814 - .989
Hip Total Rotation Supine 30º Left	.973	.860 - .992
Hip IR Supine 30º Right	.942	.786 - .987
Hip ER Supine 30º Right	.853	.436 - .967
Hip Total Rotation Supine 30º Right	.934	.756 - .985
Hip IR Prone Left	.804	.234 - .955
Hip ER Prone Left	.957	.844 - .990
Hip Total Rotation Prone Left	.887	.575 - .974
Hip IR Prone Right	.977	.913 -.994
Hip ER Prone Right	.778	.119 - .937
Hip Total Rotation Prone Right	.937	.766 - .985
Hip IR Sitting Left	.968	.814 - .990
Hip ER Sitting Left	.954	.829 - .989
Hip Total Rotation Sitting Left	.982	.932 - .996
Hip IR Sitting Right	.972	.841 - .991
Hip ER Sitting Right	.945	.789 - .986
Hip Total Rotation Sitting Right	.979	.923 - .995

Chapter 6 Discussion

The purpose of this research was to examine whether an association between hip joint ROM and lower back pain exists. To these ends individual's, with and without lower back pain, hip ROM was measured. A discussion of the group's characteristics is firstly presented. Accurate joint range measurement has proved to be a challenging endeavour. These obstacles and their effects on hip ROM values are also examined. Finally, each objective and their related findings are reviewed below.

6.1 Group Characteristics

No association was found between gender and lower back pain, meaning that men and women presented equally with the condition. Furthermore, parity was also observed between the two groups' age, BMI, Beighton scores and Baecke Work Index. The control group's Baecke Sport and Leisure Indices however, scored significantly higher than the pain group's, resulting in a correspondingly significant Total Baecke score. In the author's opinion, this may reflect true life circumstance, where symptomatic individuals suffer through pain at work in order to make a living, but participate less in sport and are more sedentary during their free time. Greater pain levels have been associated with reduced functionality (Handrakis et al., 2012).

A distinguishing attribute of this research was that there was no significant age difference between the groups and that both group's median age was in their fifties. A large number of earlier studies' cohorts were aged in their twenties (see subsections of section 2.10). Since the prevalence of osteoarthritic change increases from the age of 50 (Cibulka et al., 2017) and is thus one of the diagnostic criteria for the condition (Altman et al., 1991), an older cohort was more likely to exhibit the changes in hip mobility that were of interest to this research. A second beneficial feature was both group's similar BMI (25.00 kg/m^2 for the control group and 25.40 kg/m^2 for the pain group). This was marginally above the high norm of 24.9, ensuring the experimental group's lumbar symptoms were unlikely due to increased body weight.

Hypermobility disorders have been associated with chronic lower back pain and lumbar disc herniation (Eseonu et al., 2021; Aktas et al., 2011). Higher Beighton scores (> 4) have also been significantly linked to thinner hip capsules (Devitt et al., 2017) and is indicative of hip hypermobility (Clapp et al., 2021). The pain and control group's similar Beighton scores (2.3 and 2.31 respectively) were well below the proposed hypermobility threshold of ≥ 5 (Juul-Kristensen et al., 2017), and being of comparable value, negated the potential effect of excessive tissue mobility on the lumbar pain group's symptoms and both group's hip range measurements.

6.2 Hip ROM Measurement Results

In attempting to measure the group's hip ROM, certain methodological problems were uncovered. These obstacles were not specific to this research, but relate to the time-honoured use of certain bony landmarks and the accurate identification of the sagittal plane's neutral starting position. Historically, the greater trochanter, the most superficial point and the only feasible option, is used as the sagittal plane's axis of movement, but it's not the hip's true axis, the centre of the femoral head is. Furthermore, bulky overlying muscles and the greater trochanter's large size makes the pin-point identification of its midpoint challenging. Reproducing this axis of rotation perfectly on both sides and from person to person is impossible. The second challenge was that the greater trochanter and lateral epicondyle are at different heights above the plinth's surface. The femur's sagittal plane starting position is therefore not neutral, nor parallel to the floor. These obstacles likely presented in other studies, even though they were not directly acknowledged their effects were alluded to (Peterson Kendall et al., 1993; Sahrmann, 2002). These failings either exaggerate or undervalue the hip flexion, extension, SLR and MTT ranges (and are detailed in Appendices G, H and I below).

Consequently, the hip flexion, extension, SLR and MTT measurements need to be considered in two different ways - through two proverbial lenses. The first lens, is to accept these limitations and discuss the hip ROM results at face value (see Table 2). The study's outcomes are largely in line with earlier published guidelines (Clarkson, 2000; Peterson Kendall et al., 1993; Roaas and Andersson, 1982; Sahrmann, 2002). These are derived from the imperfect alignment of the sensor along the femur's longitudinal axis and a common but poorly controlled, non-neutral starting position. The second lens, is to discuss these error's effects, without knowing their magnitude. This inadvertently undermines the study's sagittal plane research results but opens up a conversation about the problem in the hope it will be resolved in the future. The reader is referred to the dissertation's limitation's section 7.4.1.5 outlining the challenges encountered pursuing accurate IMU placement; section 7.4.1.6 discussing the challenges with identifying hip joint neutral and to a series of experiments in Appendices G, H and I for an explanation of the effects the IMU's placement has on sagittal plane measurement accuracy. Finally, to the author's knowledge, a unique theoretical solution to this problem is presented in Appendix J. The discussion of the first lens' results appear in the paragraphs below.

This studies' hip ROM measurement results approximate those achieved in other research (Clarkson, 2000; Peterson Kendall et al., 1993; Roaas and Andersson, 1982; Sahrmann, 2002). The reader is referred to section 2.6.1, for these other research results and section 5.2, for this study's. Closer inspection of this study's "first lens" outcomes reveals relatively high hip flexion (129.63^{o}) and extension (32.04^{o}) values when compared to the AAOS's standard. The SLR value (71.00^{o}) is in a similar range to other studies; within the approximate norm of 80^{o} described by Peterson Kendall et al. (1993) and between a low mean of 66.5^{o} in a symptomatic group and a high mean of 84.4^{o} in an asymptomatic "flexible" group (Halbertsma et al., 2001). Owing to the MTT's poor reliability (Paatelma et al., 2009), normal values vary greatly for this test - ranging from 12.6^{o} of hip flexion (Van Dillen et al., 2000) to 15.5^{o} of hip extension (Beneck et al., 2018). In spite of this reputation, this researcher obtained ICC values of .954 and .922 for the left and right MTT (with knee extended) respectively. This study's MTT average (-9.10º) sits agreeably within the range of these previous research outcomes.

The study's coronal plane range outcomes has mixed agreement with earlier research. The abduction results (44.33º) almost perfectly match earlier investigations, in spite of this study's noteably poor right hip abduction ICC score. Remarkably, a normative value of 45º abduction receives widespread accord (Clarkson, 2000; Peterson Kendall et al., 1993; Sahrmann, 2002). There is however greater discord concerning adduction's normal range. This study achieved a 28.67º result, concurring with the AAOS' 30º guidline (Clarkson, 2000) and Roaas and Andersson's (1982) conclusion of 30.5º but diverging considerably from standard texts which list 10º (Peterson Kendall et al., 1993; Sahrmann, 2002) as the norm. Since this study's cohort's age sits just above the definitive osteoarthritic onset threshold, because participants with hip problems were excluded and because adduction is a gravity assisted range, this research's results are likely an accurate reflection.

Again, the transverse plane's outcomes have mixed concurrence with previous research. The prone position's measurements are discussed here, because these were the most likely quoted in other texts. The study attained results of 41.62º and 55.78º for hip internal and ER respectively. This research's greater external than IR range result is in keeping with some studies (Simoneau et al., 1998; Roach et al., 2013; Prather et al., 2010; Adegoke and Fapojuwo, 2010) and contrasts with those where IR was marginally greater (Klassbo et al., 2003). This study's outcomes also conforms somewhat with Kouyoumdjian et al.'s (2011) and Ellison et al.'s (1990) findings, where in 47.5% and 34% of their respective cohort's ER predominated, in some contrast to the 13% and 37% of their respective groups where IR prevailed. Although certain studies show virtually equal internal and ER range results (Roaas and Andersson, 1982), what may be of interest, is that this feature had a lower prevalence. It appeared in 39.5% of Kouyoumdjian et al.'s (2011) sample and in 22.67% of Ellison et al.'s (1990).

Generally, the above rotation range results diverge from notable educational texts (Sahrmann, 2002; Clarkson, 2013) and the AAOS' clinical guidelines (Clarkson, 2000) who offer equal hip internal and ER ranges, of approximately 45^{o}, as the norm. Earlier (Peterson Kendall et al., 1993) and a subsequent edition of "Muscles Testing and Function" by Peterson Kendall et al., (2005), do not even list a normal hip rotation range. Kaltenborn, (2011) stated a greater ER range (45^{o}) than IR (40^{o}), but this is likely clinically imperceptable. To their credit, a more recent edition of Maitland's text (Hengeveld and Banks, 2014) does acknowledge the effects of femoral version and presents a more realistic normal hip rotation ROM range (20^{o} – 45^{o} for IR and 30^{o} – 45^{o} for ER) but only quotes active ROM measurements. They attributed angles of less than 20^{o} IR and 30^{o} ER to shortened capsules or overactive or shortened muscles. IR and ER ranges greater than 45^{o} were ascribed to hypermobility. Considering that this study tested passive movement, an additional 10^{o} of ER range here, is likely to still be in line with their conclusions. This study's IR result is marginally higher than their upper limit of 45^{o}, assuming an additional 10^{o} is possible through passive testing. In light of these considerations, the above mentioned reference text's rotation ROM values may be in need of redress, to ensure more accurate treatment guidelines and goal setting.

6.3 Discussion of Objective 1 and 2 Determination and Comparison of the Pain and Control Group's Hip Ranges' ROM

No significant difference was found between the groups for any of the side hip movement variables (see Table 5.6). The null hypothesis was therefore confirmed. These results replicate the findings of a large number of studies that did not find a significant difference between the hip ROM of their lumbar pain and control groups. This research is somewhat unique, in that along with Tsai et al., (2010), is the the only study, to the author's knowledge, that assessed all hip ROM, namely hip flexion, extension, abduction, adduction, internal and ER. They too did not find any significant difference between their pain and control group's hip ROM. Although Tanaka et al.

(2015) were comparing the ROM of osteoarthritic and non-pathological hips in group's with and without lower back pain, they found no difference between the group's non-pathological side's hip flexion, extension and abduction ranges. Adegoke and Fapojuwo (2010) also noted no difference between their group's hip extension. No significant difference was found for MTT between groups in Handrakis et al. (2012) and Stuelcken et al.'s (2008) studies. Further, Handrakis et al. (2012), Reis and Macedo (2015) and Esola et al. (1996) also found no significant difference between their group's SLR results. No significant hip rotation range difference was found between Young et al. (2014) and French et al.'s (2015) cohorts. Four studies, Adegoke and Fapojuwo (2010), French et al. (2015), Tsai et al. (2010) and Nourbakhsh and Arab (2002) observed no difference in abduction range between their symptomatic and asymptomatic lower back groups. Lastly, although in contrast to this research, in that they both tested active hip adduction, Adegoke and Fapojuwo (2010) and Tsai et al. (2010) also found no significant difference in this range between their two groups. It should be noted that this study's adduction range result may stem from a participant selection bias. Clinically, the author has noticed increased adduction range in patients with gluteus medius tendinitis and trochanteric bursitis. As individuals with lateral hip pain were excluded from this study, participants potentially presenting with this anomaly were inadvertently excluded.

Apart from the possibility that hip ROM has no bearing on lower back pain, this author has no explanation for the lack of significance seen between the study's groups. In the same way, Handrakis et al. (2012); Stuelcken et al. (2008); Young et al. (2014); Tanaka et al. (2015); Reis and Macedo (2015) also offered no reason for their group's similar hip ROM. Adegoke and Fapojuwo (2010) attributed their group's similar hip ranges to hip treatment that the lumbar pain group received prior to testing which may have normalised any restricted ranges. Tsai et al. (2010) and Nourbakhsh and Arab (2002) also did not state a rationale for their group's hip range similarities but both found erector spinae muscle weakness in their lower back pain group. Esola et al. (1996) found no difference between their group's hamstring length and did not give an explanation thereof, they did however find that people with a history of lower back pain had an altered pattern of movement during bending. French et al. (2015) focused their discussion on a significantly reduced hip flexion range in their lumbar pain group's arthritic side but posed no explanation for their group's similar hip abduction, internal and external ranges. Although not suggested elsewhere, postural effects may play a role in the aetiology of lower back pain. This is discussed in greater detail in section 6.4 below.

As noted above, an explanation for the lack of group significance, is that lumbar symptoms may result from the interplay of relative lumbar – hip joint range flexibility, lumbar and hip muscle weakness and loads imposed. This research addresses only one of these factors. These alternate aspects have been tackled in other research though. Exploring the correlations between non-specific lower back pain and disability, Shin (2020) researched lumbar and hip's muscle strength and ROM in office workers. Lumbar flexor and extensor strength imbalances, hip joint ROM and range side asymmetries showed a correlation with pain and/or disability. In a similar fashion, asymptomatic field hockey players have exhibited greater eccentric lumbar extensor strength than symptomatic competitors (Murtaugh, 2001). Nagai et al. (2015) investigated trunk strength, lumbar and hip ROM in military helicopter pilots. Pilots need to be able to flex, extend and laterally flex in a confined, seated position to safely operate a helicopter, an activity that necessitates erector spinae strength and coronal plane flexibility. They found that their lumbar pain group had significantly reduced lumbar extensor strength, reduced lumbar lateral flexion range, lumbar rotation side-to-side asymmetry and total hip rotation side asymmetry. Weakness of these muscles and reduced range was either the cause or result of lower back pain in this group.

The timing of muscle activation is yet another consideration. Low back pain sufferers who competed in rotation related sports were shown to exhibit earlier and greater spinal rotational movement than a pain-free cohort (Scholtes et al., 2009). Esola et al. (1996) found significantly reduced lumbar movement during the middle phase of the forward bending motion in their group of individuals with a history of lower back pain. In a similar vein, individuals within different rotation and rotation-extension lumbopelvic hypermobility groups revealed no difference for hip lateral rotation range, hip lateral rotation side asymmetries, lumbopelvic rotation angle and lumbopelvic side asymmetries, but the rotation hypermobility subgroup's timing of movement displayed greater side symmetry than the rotation-extension lumbopelvic hypermobility groups' (Van Dillen et al., 2007). These findlings suggest differing motor control capacities amongst different lumbar pain groups necessitating tailored spinal muscle strengthening programmes.

Lastly, a possible reason for the lack of group significance seen, may stem from the absence from the exclusionary process of psychosocially "high risk" persons from the pain group. The biopsychosocial pain model is a systemic approach, integrating the "whole person", recognising the interaction of pain's psychological, social and biological components (Otero-Ketterer et al., 2022; Bevers et al., 2016). Since non-specific lower back pain often has no known pathological link, it is considered a neurobiological and behavioural reaction to a perceived threat rather than a disease process (Otero-Ketterer et al., 2022). These psychological factors linked to chronic lower back pain include kinesiophobia, catastrophism, anxiety, and depression (Yamada et al., 2022). Certain authors believe that psychosocial factors are a pervasive, normal consequence of both acute and chronic lower back pain disorders (O'Keeffe et al., 2018). Chronic pain states are further developed and maintained by central sensitisation (where neural thresholds are diminished by continual noxious stimuli) and neural plasticity (pertaining to central adaptations in response to behavioural, environmental and injurious change) (Bevers et al., 2016). The exclusion of participants with a higher psychosocial risk, would have enhanced the composition of the pain group, ensuring participants with more distinct biomechanically fomented symptoms.

Consequent to these results and similar findings in other studies, hip ROM does not appear to be different in people suffering with lower back pain. Further studies on the topic would help determine whether this result is definitive. Although lumbar symptoms were documented, in retrospect the omission of lumbar range measurement, hip and lumbar strength assessment and the exclusion of biopsychosocial "high risk" participants from the pain group, is a limitation of this study and its combination a consideration for amelioration in future research.

6.4 Discussion of Objective 3

Comparison of the Pain and Control Group's Side-to-Side Hip Ranges' ROM

Despite the convincingly similar hip ROM between the lumbar pain and control groups, a surprising number of side-to-side hip range variables displayed a significant difference in each of the two groups (see Tables 5.7 and 5.8). Although the control group displayed a significant side-to-side ROM difference in 5 of the 15 variables, 11 of the 15 tested variables showed significant side asymmetry in the pain group. The following variables showed a significant side difference in the symptomatic group: hip flexion; SLR; hip extension; hip adduction; internal, external and total rotation in supine 30º; internal and total rotation in prone and internal and total rotation in sitting. The control group's external and total rotation in supine 30º; external and total rotation in prone and IR in sitting variables showed a significant side difference. The pain group's effect sizes mostly varied between a small and medium effect, with medium to large effects seen between left and right SLR, ER in supine 30º, total rotation in prone, IR in sitting and total rotation in sitting ranges. Most of the control group's significant result's effect sizes were of a medium effect, with total rotation in prone having a large effect and IR in sitting a small to medium effect. This adds to the topic's body of knowledge as there is a scarcity of literature examining all hip (flexion, extension, abduction, adduction, internal and ER) ROM's side differences in groups with lower back pain (Abady Avman et al., 2019).

The complete absence of any group hip ROM differences in the first objective's findings highlights the significance found in the group's side-to-side hip ROM differences. The reason for the study's side differences may however be difficult to pinpoint - explanations offered in the past have varied in nature. One proposed cause of asymmetry is that it is the result of FAI or the early onset of arthritic change (Ellenbecker et al., 2007). Ellenbecker et al. (2007) however researched tennis and baseball players where handedness and repetitive movements could have had such an effect. A second proposal, in baseball pitchers, was related to adaptive changes in hip range, this was attributed to dominance and repetition (McCulloch et al., 2014).

Even though a significant difference was found between this study's group's Baecke sport, leisure and total activity scores, they were unlikely to have had such an effect on hip range side differences as both limbs would have been exposed to the same loading. Furthermore, any repetitive activity's effects should have been negated by the group's diversity.

What may be of interest to note, is that the lumbar pain group's asymmetrical ranges span all three planes of movement. The pain group's hip range side asymmetries presented in the sagittal, coronal and transverse planes, while the control group's only presented in the transverse plane. The control group's significantly greater left hip IR range in sitting defied explanation, although it could possibly mirror a commonly adopted cross-legged sitting position. The greater left hip ER range seen in a few of the control group's sagittal plane positions, however, should not be overlooked. Closer inspection of these asymmetries, saw a predominantly greater degree of left ER in the supine 30º and prone positions. The significantly higher left total rotation in supine 30º and prone positions is likely just a mathematical consequence of the greater left ER values and not of any specific anatomical or pathological importance. This hip feature may reflect a habitual, asymmetrical standing posture which pervades the general population. It thus presented in the control group's results, but conceivably played a bigger role in the lumbar pain group's, because of this group's three-plane-of-movement's hip range asymmetries' cumulative effects on the spine's orientation and motion (Hruska, 2017). This is discussed in greater detail below.

An assessment and treatment regimen developed by Hruska (2017) may offer a reason for the groups' detected side differences. He noted that a habitual, standing position, encourages weight shift onto the dominant leg, with the non-dominant leg planted in a forward position. As approximately 90% of the world's population are right handed (Jarry, 2021), weight shift is usually to and more readily spent over this side. The forward resting left leg and weight shift over the right leg, sees the left ASIS more anteriorly located relative to the right ASIS. This consequently places the right hip in an extended, adducted and internally rotated position with the left hip set in flexion, abduction and ER. This lengthens the left hamstrings and shortens the left ITB/tensor fascia lata and right hamstrings. The left foot's position and accompanying right side's Trendelenburg, consigns the lumbar spine to a right rotated and right laterally flexed position. Termed the left Anterior Interior Chain (AIC) pattern, this customary posture sees a series of bilateral hip and spinal motion asymmetries with changes in spinal orientation (Hruska, 2017). Prolonged positioning reduces the hips' and lumbar spine's ranges in the opposite direction (Hruska, 2017; Boyle, 2013). This posture may seem arbitrary, but has such universal adoption that it was commonly used in classical and Renaissance art to realistically capture the human form (Payne, 2020; Zucker and Harris, 2022). Given the moniker "contrapposto" (counterpose) by Italian artists, it can be seen in Fig. 6.1 below.

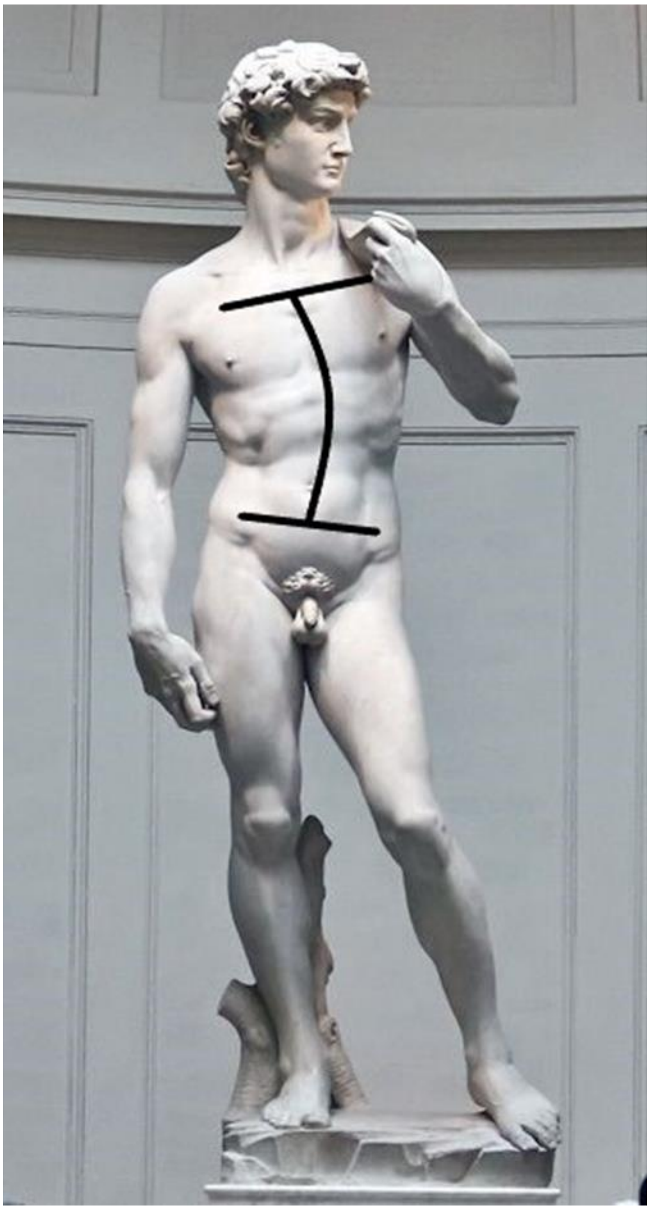

Fig. 6. 1 David by Michaelangelo. Altered image of the ubiquitous left AIC, "contrapposto" posture (Image reference: Patil, 2022).

This concept has support from a number of other spheres. Peterson Kendall et al's. (1993) text on the effects of dominance on posture shows similar characteristics, although their findings are not quite as detailed and they approach the topic from a muscle length and strength point of view. Young et al. (2014) incidentally documents a large number of studies that associated reduced hip IR in the non-dominant hip with lower back pain, but did not give an explanation for its occurrence. The concept is possibly also bolstered by the research of Janssen et al. (2010) and Kouwenhoven et al. (2006) who found that on MRI and CT examination of normal adults in the neutral position, the mid and lower thoracic spine was rotated to the right. This corroborates Hruska's belief that right spinal rotation occurs but contradicts his assertion that it takes place in the lumbar spine. Another supporting study, measured 13 healthy people's intervertebral lumbar ranges using a standing MRI and showed greater right than left intervertebral lateral flexion range at each level (Berry et al., 2019). Unfortunately, they investigated lumbar intervertebral levels only. These findings not only support the concept but also reflect the lumbar and thoracic spine's functionality. That is, the thoracic spine's relatively greater capacity for rotation and the lumbar spine's relatively greater capacity for lateral flexion (Neumann, 2017). See section 2.5.2 above.

The left AIC's asymmetrical hip range characteristics and whether their prescence was of significance in each group, is tabulated in Table 6.1 below. On closer examination of the study's hip side asymmetry ROMs, the left AIC pattern is more significantly evident in the pain than control group's results. Of this concept's eight possible asymmetrical hip side characteristics, the pain group significantly demonstrated four, while the control control exhibited one. As was established earlier, individuals with lumbar pain present more regularly with hip ROM asymmetries but this suggests that habitual, asymmetrical weight-shifted postural patterns may play a causative role. The resulting altered spinal alignment offers an additional explanation for lower back pain in certain cases. Correction of this pattern with manual techniques and exercise directed on the lumbar spine and hip joints would alleviate the problem (Hruska, 2017; Boyle, 2013) .

Table 6. 1 A Summary of the Left AIC's Characteristics and Their Presence in Each Group

Left AIC's Characteristics	Pain Group	Control Group
Greater left hip flexion range relative to the right	Yes - significant	Yes – but non-significant
Greater left hip ER range relative to the right (30^{o} sagittal plane)	Yes - significant	Yes - significant
Greater left hip abduction range relative to the right	No – left and right range equal	No – left and right range equal
Reduced left iliopsoas length relative to the right	Yes - but not significant	No – non-significantly reduced on the right
Greater left SLR range relative to the right	Yes - significant	Yes - but not significant
Greater right hip extension range relative to the left	No – left range is significantly greater	No – left range is non-significantly greater
Greater right hip adduction range relative to the left	No – left range is significantly greater	No – left range is non-significantly greater
Greater right hip IR range relative to the left (30^{o} sagittal plane)	Yes - significant	No – left and right range essentially equal

Although side dominance was not recorded in the study's methodology and therefore does not factor in the results, it may have enhanced them. This omission is a limitation of this study's design and should be a consideration in future research where hip side differences are being investigated, even when dominance is not a direct concern of the research. A retrospective analysis, using the study's data but obtaining further information on dominance from the participants, may give a clearer picture. This is the first time, to the author's knowledge, that an examination of hip range results has been completed in this manner. Further research investigating this phenomenon is necessary. Moreover, it is of importantance to note that this analysis was performed using the 30° supine external and IR data. This was because the left hip is often placed in flexion and ER in standing – the 30° supine IR results were also used for the comparison but have arguably been included incorrectly, as the posture's right hip stance is more closely akin to the prone IR position. Making use of the prone rotation results (instead of the 30° supine) in this analyses had a less favourable outcome, in that the pain group's left hip ER was not significantly greater than the right's and the right hip's IR was not significantly greater than the left's in this position. This could suggest that the 30° supine position is best used to diagnose this condition. This may be another feature unique to this research, in that it may have uncovered a test sensitive to diagnosing left and right AIC in persons presenting with lower back pain. Further investigation is also necessary in this regard.

Other singular side asymmetries seen in the pain group's sagittal and coronal plane ranges are also of importance. These asymmetries are likely to elicit symptoms depending on the functional activity being performed. Hip movement assymetries may cause abnormal rotation/torsion of the lumbar spine as these specific hip ranges are drawn upon (Sahrmann, 2002). For example, on rocking forward during the initial stages of rising from a chair, symmetrically reduced hip flexion causes the lumbar spine to compensate and flex excessively in the sagittal plane; asymmetrical hip flexion range causes a torsion of the pelvis and the lumbar spine during this same movement. This logically causes symptoms in both instances, but for different reasons. Examining activities of daily living with the single or combined hip movement deficits in mind, would help identify insidious mechanisms of injury and aid treatment technique selection.

In light of objective 2 and 3's outcomes, the clinician should consider preferentially shifting their attention to the treatment of hip range asymmetries in patients with lower back pain rather than only targeting normative ranges. Remaining cognisant of side dominance would also be of value. Identifying the side which represents the normal range may be problematic (Hogg et al., 2018), although taking a thorough subjective history may help to resolve the issue to some degree.

6.5 Discussion of Objective 4 and 5

To Determine Whether There is an Association Between Hypomobile and Hypermobile Hip Ranges and their Coupled Symptomatic Lumbar Ranges

6.5.1 Lumbar Flexion and SLR Coupling – Mean of Left and Right SLR Length Pairwise Comparisons

Although the symptomatic lumbar flexion subgroup displayed the lowest mean SLR length range and the asymptomatic lumbar flexion subgroup the highest, no significant differences were found across the three subgroups. This concurs with the wider pain and control group's SLR similarity but diverges from the wider groups' side differences which saw significance in the pain group and non-significance in the control. This objective's result suggests that the left and right's averaged hamstring length does not affect lumbar symptom generation. As both hamstrings act during bending it was thought prudent, practical and realistic to take an average, but this may disguise the reality that side asymmetries and their associated spinal torsions are key. Furthermore, this conclusion is hampered by the lack of testing of the lumbar spine's flexibility, strength and sequencing of movement. These have been postulated to be factors in the propagation of low back pain with bending (Johnson and Thomas, 2010; Esola et al., 1996) and are outlined in section 6.3 above.

6.5.2 Lumbar Flexion and Hip Flexion/Squat Coupling – Mean of Left and Right Hip Flexion Range - Pairwise Comparisons

Once again, squatting was not significantly linked to lower back pain with similarity seen across the three subgroups' median hip flexion range. This result was limited by the low number of symptomatic lumbar squatting cases, however this may be due to the position's inherent flexibility (Zinman, 2022). Most people squat into combined hip flexion, abduction and ER. Although the hip flexion component tightens the posterior capsule, which in isolation would likely cause posterior pelvic tilt, lumbar flexion and potential symptoms, the combined hip abduction and ER components of the movement, likely releases the posterior capsular tissue and distances the femoral neck and acetabular rim. This possibly unloads the spine enabling asymptomatic movement and forms the basis of safe lifting technique (Government of Alberta, 2022). It is also used clinically by Sahrmann (2002) to avoid impingement when treating hip flexion deficits. This contradicts this paper's earlier assertions that combined flexion, abduction and ER represents a hip closed pack position (see section 2.4.3.7 above). It is possible though that the combined position's effects take hold later in the range. In retrospect, directing participants in this study to squat with their thighs in the sagittal plane may have garnered different results.

6.5.3 Lumbar Extension and Hip Extension Coupling – Mean of Left and Right Hip Extension Range Pairwise Comparisons

Once more, no statistical difference was found between the subgroup's mean hip extension range, suggesting that hip range has no bearing on lumbar extension symptom generation. This mirrors the results of a number of studies (Tanaka et al., 2015; Tsai et al., 2010) but holds considerable more weight with this analyses' respectable group sizes. It may also have greater sway because of these other studies' questionable methodologies: where the methodology was not stated (Tsai et al., 2010) and where participants were measured on occasion in side-lying (Tanaka et al., 2015) or in supine (Adegoke and Fapojuwo, 2010). As significance was found between the study's wider pain group's side-to-side hip extension ranges, this result may be a consequence of using an average. What may be of some interest, is that the control subgroup and the asymptomatic lumbar extension pain subgroup's mean hip extension range were almost perfectly equal, while the symptomatic lumbar extension pain subgroup's was marginally less.

6.5.4 Lumbar Extension and MTT Coupling – Mean of Left and Right Hip Iliopsoas Length Pairwise Comparisons

The symptomatic lumbar extension pain subgroup had the smallest mean iliopsoas length, followed by the control subgroup and then that of the asymptomatic lumbar extension pain subgroup. The asymptomatic subgroup's range was significantly greater than both the symptomatic and the control subgroup's. In the past MTT results have been dismissed due to poor reliability (Paatelma et al., 2009), but these outcomes are strengthened by this study's high MTT reliability scores (.954 for the left hip and .922 for the right). These findings suggest that people with greater iliopsoas length are not predisposed to pain on lumbar extension, but may have been undermined by the fact that no difference was found between the symptomatic and control subgroup's means.

The significance found between the subgroups has an interesting feature. The symptomatic subgroup's mean range of -7.79^{o} has an association with lumbar extension pain. Even though there was no significant difference between the control and symptomatic subgroup's ranges, the control subgroup's participants were pain-free with a range of -8.05^{o}. Although they suffer with chronic lower back pain, members of the asymptomatic pain subgroup, with a mean MTT range of -11.93^{o}, were also pain-free when extending their lumbar spines. It may be a tenuous argument, in light of the previous discussion on the role of lumbar range, hip and lumbar strength and movement sequencing on pain propagation, but this result suggests a possible symptom-linked ROM threshold. Namely, that once this study's MTT range reached approximately (minus) 8º, the lumbar extension range became asymptomatic. This value closely correlates with the study's MTT mean result of -9.10º. This range threshold may serve as a clinical guidline for the treatment of symptomatic lumbar extension where no instabilities exist.

It is also surprising that the iliopsoas length differed significantly between the asymptomatic lumbar extension pain subgroup and symptomatic lumbar extension pain subgroup and the control subgroup and the asymptomatic lumbar extension pain subgroup, when this proved not to be the case with the subgroup's hip extension range. Since lumbar extension is both hip extension and iliopsoas length's coupled lumbar range, this inconsistency is further pronounced by the fact that the exact same subgroup samples were used in both analyses. Furthermore, both hip extension and iliopsoas length subgroup's ROM results displayed the same pattern, namely that the asymptomatic lumbar extension pain subgroup had the greatest hip range, followed by that of the control subgroup and then that of the symptomatic lumbar extension pain subgroup. This may be a consequence of differing assessment methodologies. The lumbar spine's position is fixed during MTT testing, but it may have compensated with lumbar extension and/or rotation during hip extension testing because its position was not controlled. This possibly produced the statistically non-significant hip extension results seen across the subgroups.

6.5.5 Lumbar Left Lateral Flexion and Right Hip Adduction Coupling - Pairwise Comparisons

Lumbar left lateral flexion and right hip adduction were analysed together, as this hip's adduction's smaller coronal plane range was more likely to be the limiting factor than the left hip abduction's relatively greater ROM. No significant differences were however found between the three subgroup's right hip adduction range. This follows the earlier findings, that the study's wider groups' right adduction ROM mirrored normal values and showed no significant difference between them. This augments the meager amount of literature exploring the effects of adduction range on lower back pain (Abady Avman et al., 2019). It is the author's clinical experience that individual's presenting with gluteus medius tendinitis and trochanteric bursitis have increased hip adduction range, with the resulting Trendelenburg causing associated lumbar symptoms. As these conditions were study exclusions, people with this hip range abnormality may have inadvertently been excluded.

The analysis above and conclusions drawn are academic, and essentially moot points. In standing with the feet shoulder width apart, 10.6° hip abduction and 10.1° adduction range have been observed in a healthy, male sample during lateral flexion (Tojima et al., 2016). They also found that with a mean of 29.5° of lumbar lateral flexion range, and a lumbopelvic rhythm ratio indicating that for every degree of hip abduction and adduction, the lumbar spine laterally flexed 2.4°, the lumbar spine moves more than the hips during lateral flexion to maintain balance. Other authors have found a similar association (Chang et al., 2018). Consequently, with approximately 35° and 20° of available but unused hip abduction and adduction range respectively, any restriction of these hip ranges cannot and do not have an influence on lumbar lateral flexion. This trait may however be useful in lumbar spine assessment - as this is the only lumbar range where hip ROM has no influence, symptoms elicited with side-bending (and feet shoulder width apart) are specific to the spine.

6.5.6 Lumbar Right Lateral Flexion and Left Hip Adduction Coupling Pairwise Comparisons

Similarly, as for lumbar left lateral flexion and right hip adduction coupling above, left hip adduction range showed no significant difference between the subgroups. The opinions and discussion in section 6.5.5 are applicable here too.

6.5.7 Lumbar Left Rotation and Left Hip IR, Right Hip ER (Ranges Equal) Coupling - Pairwise Comparisons

No significant differences were found between the three subgroups', left lumbar rotation limiting, averaged left hip internal and right hip ER's (hip ranges equal) medians. Further, no clear conclusions can also be drawn from these results as they were marred by their small sample sizes. Although the additional splitting of the subgroups into hip anteversion, retroversion and equal hip range patterns reduced the studies' statistical power, it was deemed necessary. Grouping participants with differing hip version variations together nullifies their effects on hip rotation range leading to distorted results. Following Ellison et al.'s (1990) findings that individuals with retroverted hips were significantly more likely to suffer lower back pain, hip version variations should be recognised and researched seperately considering the different "beasts" that they are. In spite of the large number of studies researching hip rotation's association with lower back pain, this generally unacknowledged hip trait may account for the frequent non-significant results seen (see section 2.10.5 above). Clearly, future studies researching hip version's effects on lumbar symptoms should employ appropriate group sizes to ensure statistical power.

6.5.8 Lumbar Left Rotation and Left Hip IR, Right Hip ER (IR<ER) Coupling - Pairwise Comparisons

Here too, the subgroup's, left lumbar rotation limiting, left retroverted hip's range's medians showed no significant difference. Disproportionate and small sample sizes undermined this result. As discussed in section 6.5.7 above, future research would do well to recruit larger cohorts and study hip version traits in isolation rather than grouping participants with differing version types together.

6.5.9 Lumbar Left Rotation and Left Hip IR, Right Hip ER (IR>ER) Coupling - Pairwise Comparisons

It was not possible to perform an analysis of whether the subgroup's right hip anteversion had an effect on left lumbar rotation symptoms. Only one member of the control subgroup had right hip external range limiting, left lumbar rotation. Here right hip ER was 16º less than the participant's left hip IR. Four members of the asymptomatic lower back pain subgroup had relatively less right hip ER and none of the symptomatic lower back pain subgroup's participants demonstrated hip anteversion. As a result, the sample sizes prevented any such analysis.

6.5.10 Lumbar Right Rotation and Right Hip IR, Left Hip ER (Ranges Equal) Coupling - Pairwise Comparisons

Again, no significance was found between the three subgroups', right lumbar rotation limiting, averaged right hip internal and left hip ER's (hip ranges equal) medians. The opinions outlined in section 6.5.7 above, pertain here too.

6.5.11 Lumbar Right Rotation and Right Hip IR, Left Hip ER (IR<ER) Coupling - Pairwise Comparisons

The subgroup's, right lumbar rotation limiting, right retroverted hip's range's medians showed no significant difference. The views expressed in section 6.5.8 above, apply here.

6.5.12 Lumbar Right Rotation and Right Hip IR, Left Hip ER (IR>ER) Coupling - Pairwise Comparisons

As before, small sample sizes prevented the analysis of whether relatively diminished left hip ER limiting, right lumbar rotation, was different between the subgroups. Only one control subgroup participant and three pain group volunteers with asymptomatic, right lumbar rotation presented with anteverted hips. None of the participants with symptomatic right lumbar rotation had femoral anteversion.

In summary, generally hip ROM appear to have no effect on their coupled lumbar range's symptoms. Of all the lumbar ranges investigated, only iliopsoas length showed a significantly reduced range between the symptomatic and asymptomatic lumbar extension pain subgroups. This result however is undermined by the lack of significance between the symptomatic lumbar extension pain subgroup and the control subgroup. It needs to be stressed that small sample sizes curtailed this study's findings, further research with larger cohorts are necessary to draw confident conclusions.

6.6 Discussion of Objective 6 and 7
To Determine Whether Differing Sagittal Plane Positions Affect Hip Rotation ROM

Although, rotation has traditionally been tested in the 0^o and 90^o positions, this is the first time, to the author's knowledge, that rotation has been tested in a 30^o sagittal position. While skeletal morphology is strongly linked to hip ROM (Shin et al., 2020), this study's varying sagittal plane results, suggests a capsular influence too. Making use of the entire cohort for this analyses bolstered its results.

Both left and right hip ER range varied significantly between each of the three sagittal plane positions. The same pattern was seen bilaterally, that is ER range was least in sitting, followed by prone and was greatest in supine 30º. Of the three sagittal plane positions, the ER supine 30º's greater range may be explained by iliofemoral ligament slackening and skeletal morphology in this position. These significantly different results have a bearing on the traditionally interchangeable usage of prone and sitting positions for hip ER assessment. Certain individuals could present with a clinically relevant difference across the two position's ER range. With mechanisms of injury in mind, the aspiring clinician would be wise to examine rotation in different sagittal positions to recognise any relevant joint restrictions. This would enhance technique selection, affording improved treatment outcomes (Maitland, 1986).

Left and right hip IR range varied greatly across the three sagittal plane positions. It is for this reason that capsular restrictions are believed to be playing a role. Left IR ROM showed no significant difference between the prone and sitting positions but they were significantly different on the right. Furthermore, on the left side, supine 30º had significantly less IR range than both the prone and sitting positions but on the right, the supine 30º position displayed significantly greater IR range than the sitting position's and was marginally greater than the prone's IR range. On the right side, sitting again demonstrating the significantly smallest range, followed by prone and supine 30º. In light of the right side's IR positional pattern and the bilateral ER sagittal plane positioning results, this may represent the norm.

Previous research, looking at the sagittal plane position's effects on hip rotation range, has had varying outcomes. Young et al. (2014), Ellison et al. (1990) and Kouyoumdjian et al. (2011) found no significant difference between their respective prone and sitting position's rotation ranges; while Aefsky et al. (2016), Simoneau et al. (1998) and Han et al. (2015) did find a significant difference. As in this research, these studies (Aefsky et al., 2016; Simoneau et al., 1998; Han et al., 2015) generally found greater hip internal and ER range in prone than in sitting. Earlier research attributed the prone position's greater rotation ranges to its testing in a gravity assisted position, where the sitting test position's were gravity bearing (Han et al., 2015). This study refutes this argument, as the supine 30^o position's gravity bearing results had greater ROM values than that of the prone position's.

Generally, the supine 30^o position produced significantly greater hip internal and external ROM than the prone and sitting positions. This is most likely because the position produces a relatively loose pack joint position (Kaltenborn, 2011). Of the three sagittal plane positions, supine 30^o delivered the greatest left hip ER and right hip internal and ER ranges. Consequently, it is both surprising and conspicuous that supine 30^o's left hip IR ROM was significantly reduced. As the ICC values for all these ROMs span from .778 to .977, this result may not be an aberration. Again it may reflect the left AIC pattern, noted earlier to have had a larger effect in the supine 30^o position. Prolonged standing, with weight shift to the right, sees prolonged positioning of the left leg in ER with a resulting loss of IR range. Of the three sagittal plane hip rotation assessment positions, the supine 30^o position appears to be the most sensitive in diagnosing this habitual, asymmetrical pattern. This observation is supported by the significantly greatest left hip ER range; the significantly least left hip IR range; and the (marginally non-significant) greatest right hip IR range in this position. This hypothesis was however undermined by the significantly greatest right hip ER range found in the supine 30^o position - had it been perfectly sensitive, the supine 30^o position would have revealed the significantly least right ER range. These results may also explain why objective 4 and 5's lumbar rotation-hip rotation coupling analysis, using *prone* hip rotation's ranges for the analysis, displayed non-significant results. These conclusions emphasise the need for further research into this subject. Should future research confirm these findings, it would reinforce the need for the inclusion of hip internal and ER range measurement in the supine 30^o position in individuals with non-specific lower back pain. This may be best performed with an IMU, as small asymmetries of range may be pertinent.

In all three sagittal positions, ER's greater relative (to IR) range demonstrated this wider group's tendency to hip retroversion. ER in prone was 57.15^o on the left and 54.42^o on the right (a difference of 2.73^o). Left IR in prone was 42.42^o, and 40.82^o on the right (a difference of 1.6^o). ER in supine 30^o was 62.15^o on the left and 57.54^o on the right (a difference of 4.61º). IR in supine 30º was 40.76º on the left and 42.58º on the right (a difference of 1.82º). ER in sitting was comparatively the same on each side, 51.05º on the left and 51.79º on the right (a difference of 0.74º). The sitting position's IR range was 42.97º on the left and 39.00º on the right (a difference of 3.97º). Most of these assymetries' magnitude and the side on which they occur may be explained by the habitual, standing weight shift posture. The bracketed side differences also illustrate the supine 30º position's greater sensitivity to identify these side asymmetries. Its ER side difference was greater than that of the prone and sitting position's and its IR side difference was greater than that of the prone position's. Although, it should be noted that no statistical analysis was performed to determine significance. The sitting position's greater IR range side difference countered this trend. This greater IR side difference and larger left IR range, may relate to an oft-used cross-legged sitting posture but the author has not been able to find a specific link for this observation.

The generally lower hip internal and ER ranges in sitting, also casts doubt on assertions that the hip capsule becomes lax and unstable in hip flexion (Kapandji, 2011; Martin et al., 2008), supporting the opposing view (Van Arkel et al., 2015; Fuss and Bacher, 1991). It may be purely circumstantial that hip dislocations occur in hip flexion. Namely, hip joint dislocation in motor vehicle accidents occurs not because of hip flexion joint laxity, but because of incidentally and uniquely large forces directed to the joint in that circumstance. A point however should be made, that the position of hip flexion and the combined position of hip flexion, abduction and ER may not be the same. The combined position may indeed create ligament laxity, unloading the spine in the squat position.

These findings of a significant difference between the hip rotation's range in the three sagittal plane positions may have other implications for clinical assessment and treatment. It generally suggests that hip rotation range is position specific and that assessment positions can not be used interchangeably. Previously noted hip rotation side asymmetries and sagittal plane positioning effects, indicate the role of dominance on hip rotation range. Making use of a supine 30º position to assess hip rotation ROM may help to identify handedness' effects on the range. Hip version abnormalities should see a symmetrical presentation, an asymmetry is likely caused by another factor - postural, pathological or traumatic to name a few. Theoretically, noting these combined hip positions' endfeel could possibly help identify the cause and in turn dictate their management: a restricted combined hip range with a capsular endfeel would warrant adaptation of a joint mobilisation technique, while a bony endfeel may suggest hip FAI and referral to an orthopaedic surgeon.

Lastly, fully appreciating these unique sagittal plane hip range restrictions may give insight into a purported lower back mechanism of injury. Lumbar spines are often injured in combined flexion and rotation (see section 2.5.4). This has been attributed to gapping of the facets and torsional stresses on the disc in this position, but restrictions in this position's coupled hip rotation may also be key. As seen here, an unexpected and possibly widespread significantly reduced left hip IR in 30^{o} of flexion may be relevant. Treating the specific hip range limitation may find resolution of the lower back symptoms and minimise recurrence.

Chapter 7 Conclusions and Recommendations

7.1 Conclusions

The study's first objective saw the measurement of passive hip ROM. The total cohort's (lumbar pain and control group's) hip ROM values were collated for the study's hip range results. These outcomes approximate those achieved in other research and adds to the topic's body of knowledge. Indeed historically and in this research study, certain inaccuracies exist in sagittal plane hip ROM measurements. As technology improves, identifying and defining a sagittal plane hip neutral starting position will enhance these interests. Furthermore, wider recognition of differing hip rotation and version patterns is necessary. Contrary to normal guidelines, equal hip IR and ER range is uncommon.

The comparison of the pain and control group's hip ROM showed no significant difference, indicating that hip ROM is no different in people suffering with lower back pain. In spite of the convincingly similar group hip ROM, a number of side-to-side hip range assymetries displayed a significant difference in each of the two groups. Although this trait was evident in the control group, where 5 of the 15 variables displayed a significant side-to-side ROM difference, 11 of the pain group's 15 tested variables showed significant side asymmetries. The effect sizes for these 11 significant variables varied between a small and medium to large effect. These side asymmetries presented in the lumbar pain group's sagittal, frontal and transverse planes of movement but was only evident in the control group's transverse plane. One potential explanation for these side hip range asymmetries may be the widespread adoption of leg dominant, weight-shifted standing postures (left AIC or right AIC). This posture's common usage may explain why it was observed in control group participants, but it should be noted that its traits presented more widely in the pain group's participants. As it is believed to cause hip range asymmetries and spinal malalignment (Hruska, 2017), further research is necessary to shed light on its role as a propagator of lower back pain.

Mirroring the study's findings that the group's hip ROM were similar, in general the symptomatic lumbar pain subgroup's coupled hip ROM were not significantly reduced or increased when compared to those of the asymptomatic lumbar pain or control subgroup's. These conclusions were undermined by small sample sizes in certain instances. The one exception was the asymptomatic lumbar extension pain subgroup's significantly greater iliopsoas length when compared to that of the symptomatic lumbar extension pain subgroup's and the lumbar extension control subgroup's. This result was diminished somewhat by the similarity of the symptomatic lumbar extension pain and lumbar extension control subgroup's iliopsoas length. These outcomes suggest the possibility of an optimal range and that a symptom-linked threshold exists. It also proposes that factors, other than hip ROM, are active in non-specific lower back pain syndromes.

Lastly, the objective comparing hip rotation ROM in three different sagittal positions, found both left and right hip ER range varied significantly between each of the (0^o, 30^o and 90^o) positions. ER range's pattern: being least in sitting, followed by that in prone and being greatest in supine 30^o, presented bilaterally. Right hip IR was somewhat similar to ER, in that it was marginally greatest in supine 30^o, followed by that in prone, which had a significantly greater ROM than the sitting position's. In contrast, left IR range was less consistent. Namely, it was equal in the prone and sitting positions and both of these had a significantly greater range than that of the supine 30^o position. This may possibly be demonstrating the supine 30^o position's greater sensitivity in identifying the left AIC pattern, since the pattern proposes that left hip IR be reduced. This in turn, suggests the supine 30^o position's potential strength in identifying dominance induced lumbar pain syndromes.

This study helps to underline the specificity of hip ROM's role in lumbar pain syndromes. Although well intentioned, this is likely the reason that studies using generalised hip treatment protocols in the management of lower back pain have poor outcomes (Burns et al., 2021). The detailed assessment and identification of specific asymmetrical hip ranges and linking these to symptoms and physiological or functional movement faults, is paramount. The focused treatment thereof might garner improved results. However, the isolated address of hip ROM disorders would likely also be found wanting. As discussed, the clinician would do well to equally identify any associated intervertebral joint stiffness and instabilities, hip-lumbopelvic movement sequencing faults and lumbar and hip muscle weaknesses. As lumbopelvic-hip complex diagnostic classifications and their accompanying treatment protocols improve, it is the author's hope and belief that the phrase "non-specific" lower back pain will one day be retired, interred and archived into the medical historical record.

7.2 Clinical/Practical Recommendations

7.2.1 General Clinical/Practical Recommendations

Since the AAOS published their normal hip ROM guidelines in 1965 (Clarkson, 2000), certain research has shown that hip internal and external ROM are often unequal. Opinion varies, with the prevalence of equal side ranges extending between 22.67% (Ellison et al., 1990) and 39.5% (Kouyoumdjian et al., 2011) of the population. Updating these guidelines and drawing attention to the differing hip anteversion and retroversion categories would further the interests of hip assessment and both hip and lumbar diagnostics.

In patients presenting with the condition, this study suggests that hip ROM should be incorporated into the assessment and treatment of non-specific lower back pain. Without further evidence, it is unlikely that symmetrically diminished coupled hip ranges should be ignored, but there is rather a stronger case for the focus of assessment and treatment on hip range side-to-side assymetries. Linking these hip ROM faults to functional activities would help the clinician understand aetiological forces and mechanisms of injury, negating or curbing future episodes. Incorporating the 30^{o} supine position in hip rotation assessment may help identify covert standing, weight shifted postural abberations, guiding lumbar and thoracic technique selection when spinal rotational malpositions are difficult to identify. Addressing the faulty hip hypomobility or hypermobility components of a symptomatic physiological lumbar range first, clarifies and aids identification of any lumbar intersegmental movement faults, focusing treatment and enabling quicker resolution of the condition.

The significant changes seen across all hip ER and most of the IR ranges with differing sagittal plane positions, suggests that hip rotation range is position specific and that measurements in one position are not generalisable to others. It is not really surprising that significance was found between the rotation ranges of the three sagittal positions bilaterally. Any combined rotation position would logically see a different range when compared to a neutrally positioned one. Should technology allow, clinical testing of three plane combined movements may identify profoundly different side range restrictions. This would help shed light on mechanisms of injury and guide technique selection.

Generally, the supine 30^{o} position produced significantly greater hip IR and ER ROM. This may be a clinically useful antalgic position and may be of benefit when performing hip joint traction and mobilisation (Kaltenborn, 2011). This could be because the position produces a relatively loose pack joint position as it does most closely approximate Kaltenborn's (2011) hip "resting position". Namely combined ≈ 30^{o} hip flexion, ≈ 30^{o} abduction and slight lateral rotation. This appears to be inadvertently corroborated by Fuss and Bacher (1991) who showed that no specific ligament is taut in the combined position of approximately 40^{o} flexion, half abduction and neutral rotation. Performing grade I and II accessory glides in this position may reduce pain by reducing muscle activity; stimulating mechanoreceptors and central pathways; initiating changes in biomarkers; increasing the viscosity of synovial fluid and contributing to central pain inhibition through activation of the sympathetic nervous system (Navarro-Santana et al., 2020; Maitland, 1986; Anggiat, et al., 2020). Further, the position enables greater joint distraction as the capsule is in an unconstrained state (Anggiat et al., 2020).

Dominance appears to affect habitual standing postures which in turn affects hip rotation ROM. The supine 30º position appears to be most sensitive in identifying the effects of habitual, weight shift in standing's effects on hip rotation range and should be used as such in its assessment. Hip version would likely have a symmetrical presentation, consequently any hip rotation range asymmetries are likely due to, amongst others, postural, pathological or traumatic factors. Joint endfeel in turn, should theoretically help the clinician determine whether any recognised restrictions are due to a skeletal fault or of soft tissue origin.

Drawing from this research's conclusions, hip ROM does not appear to be the defining factor in lumbar symptom provocation. The clinician is encouraged to also fully examine the abdominal and hip musculature's strength to determine any role that it may be playing in the patient's condition.

Although not mentioned by other researchers, it is the author's observation that a lower Beighton score makes end of range easier to identify as the reduced tissue elasticity provides a more distinctive endfeel. Supple individuals may offer unexpected ROM that an examiner then inaccurately records. When assessing hypermobile patients, particular attention should be made to joint endfeel to ensure accurate outcomes. Movement compensations are also more likely in this group, calling for greater control thereof. Muscle tissue may tolerate additional stretch on subsequent trials, affecting the results of muscle limited ranges, such as SLR. On assessing participants with high Beighton scores and having executed these precautions, a greater statistical range result (across the three trials) should not be dismissed as errors, instead it may be prudent to regard them as true reflections of the person's tissue type.

Lumbar lateral flexion being the only range independent of hip ROM effects, is of benefit in lumbar spine assessment. Symptoms elicited with side-bending are specific to the spine. This would assist with differential diagnoses. Furthermore, observation of the lumbar curve during this movement (Sahrmann, 2002) and side-bending PPIVM assessment (Maitland, 1986) may give indications of hypermobile and hypomobile intervertebral segments.

7.2.2 Hip Version's Effects on Hip ROM Measurements

In the clinical setting, a means for screening (Uding et al., 2019) and identifying femoral and acetabular version would be of value. This would not only help in the diagnosis of different hip pathologies, which have been distinctly and independently linked to femoral and acetabular anteversion and retroversion (Chadayammuri et al., 2016; Uding et al., 2019), but would also facilitate the development of preventative treatment strategies and reduce costly radiological studies (Guanche, 2016). Both femoral and acetabular skeletal morphology have been shown to be instrumental in determining hip ROM(Shin et al., 2020). Historically, Craig's Test and hip ROM have been used to this end (Uding et al., 2019). A comparison of hip ROM and Craig's Test to MRI measurement of femoral version, found that either of the two could be utilised for the clinical screening of femoral version; although hip rotation difference (subtracting ER ROM from the IR ROM) in neutral had the higher correlation with MRI (Uding et al., 2019).

This calculation, namely subtracting hip ER from IR range, has been used in the past (Kozic et al., 1997; Hogg et al., 2018) but has justifiably been acknowledged to "estimate" femoral version (Howard et al., 2011). This was because the method is hampered by its development in a paediatric cohort (where greater femoral version angles predominate) and the radiographical techniques it was validated against, do not fare well when compared to computed tomography imaging and cadaveric femora (Howard et al., 2011; Kuo et al., 2003). Furthermore, as this calculation does not consider and distinguish acetabular version, the result is rather an indicator of combined femoral and acetabular version. In this vein, it should be noted that they (Uding et al., 2019) did not evaluate acetabular version, but concluded that a difference of 20º between internal and ER (in both the 0 and 90º positions) is a good, conservative clinical indicator of femoral version.

Despite some of these concerns, passive hip rotation measurements have been shown to "predict" femoral and acetabular version (Chadayammuri et al., 2016). They compared CT scan analysis of 221 participant's hips (normal, FAI and with/without acetabular dysplasia) with a clinical passive hip ROMassessment. In isolation, femoral anteversion and acetabular anteversion significantly increased hip IR (in both 0º and 90º hip flexion positions) and saw the least ER range – the converse was true for combined femoral and acetabular retroversion. Similarly, femoral anteversion significantly reduced hip ER, however acetabular version did not have significant effects on this range. As such, ER range (at 0º hip flexion) was found to be more dependent on femoral torsion than acetabular version, and believed to be limited by impingement between the greater trochanter and the ischium rather than the femoral neck and posterior acetabulum. Hip flexion range was not affected by femoral torsion but acetabular retroversion did significantly reduce the range. Combined femoral and acetabular anteversion resulted in the greatest hip flexion range, while combined femoral anteversion and acetabular retroversion saw the least. Hip abduction was not affected by either femoral or acetabular morphology. These results have more recent corroboration (Shin, 2020). They found combined femoral and acetabular version increased hip flexion and IR and reduced ER and that isolated femoral anteversion decreased ER.

7.2.3 Cam and Pincer Lesion's Effects on Hip ROM Measurements

Cam lesions have been shown to have a greater effect on hip flexion than IR range. They significantly reduce hip flexion regardless of the degree of femoral version, also significantly reducing IR in hips with femoral anteversion (Kraeutler et al., 2018). In spite of this, the authors concluded, that femoral version had a significantly greater effect on hip IR range than Cam lesions did. This conclusion was corroborated by

Uding et al., (2019) who found that there was no correlation between Cam morphology and hip IR (at 90º).

In a second similar study, with the added advantage of pincer lesion inclusion, Shin et al. (2020) researched the effects of femoral and acetabular pathomorphology on hip ROM. Unfortunately, they looked at hip flexion and rotation ranges in the 90º position only. Uniquely, they found Cam lesions significantly reduced IR range but had no effect on hip flexion and that a greater femoral neck- shaft angle increased ER. In contrast to Kraeutler et al. (2018), who found that Cam lesions decreased hip flexion, they (Shin et al., 2020) observed acetabular pathomorphology solely reduced hip flexion, and therefore came to the conclusion that both femoral and acetabular lesions have an impact on this range.

7.3 Recommendations for Future Research

Applying a substantial force during passive hip range assessment to ensure end range, may inadvertently correct a restriction in the ROM. On a number of occasions, the author noted differing resistance through the range on the left and right side, to then surprisingly discover the results were similar. Although practically challenging and vulnerable to biases, an avenue for future research may delve into the measurement of the onset of joint resistance and joint end range in symptomatic and asymptomatic individuals. What Maitland (1986) referred to as R1 and R2. Analysis of the difference between these two positions, would offer information about the scale and onset of resistance in the hip joint's range. This may shed light on differences between experimental and control groups which have previously been missed.

The effects of a non-neutral starting position on hip sagittal plane range measurement appears to have been overlooked in the literature. The subject is usually managed with the use of a control group, but is relevant when constituting normal values, reconciling differences between Thomas Test and hip extension results and making functional diagnoses. With the technological strides in joint range measurement, there is a need and possible capacity for these failings to be addressed.

Besides measuring hip range and noting any coupled lumbar complaints, in order to fully appreciate lumbar-hip relative flexibility, future research would do well to also measure lumbar range as well as perform a hip and lumbar strength assessment. Determining a link between these factors would help focus the treatment of non-specific lower back pain.

To the author's knowledge, measuring hip rotation in the 30º sagittal position has not been attempted before. This offers the clinician insight into a joint range limitation previously unavailable, assisting not only with diagnoses but also treatment of lumbar and possibly hip conditions too. Additional study of this position's ROM would help establish a normal range. Further hip rotation testing in different sagittal positions, between 0º and 90º, could potentially produce guidelines which would enable the clinical diagnoses of, for example, hip Cam and Pincer lesions or hip instabilities, where radiological investigations are unavailable or too costly.

Additionally, research on standing, weight shifted postures and their effects on hip range, lumbar posture and ROM and lower back pain requires attention. Evaluation of hip rotation in the prone, sitting and particularly 30º supine positions may aid diagnostics and offer additional insight into malpositioned, rotated lumbar spines generally hidden in the clinical environment. This would in turn help to clarify the relationship of coupled hip range, lumbar movement and lower back pain, explaining confusing patterning. For example a rotated, malpositioned spine, may elicit pain when bending, but not with lumbar rotation, falsely implicating other hip ranges. This would also be best investigated with the inclusion of lumbar range, hip and lumbar muscle strength and leg dominance assessment.

Future research exploring the coupling of hip and lumbar rotation effect's on lumbar symptom generation, should consider sorting their participants into normal (equal) version, anteverted and retroverted subgroups. This would help clarify any effect version has on lumbar symptoms. An additional avenue for exploration would be to investigate lumbar rotation-hip rotation coupling using the supine 30^o rather than the prone position. This may uncover an association between the two. Further study considering standing, weight shifted posture's effects on lumbar pain would best be examined using the supine 30^o position, noting leg dominance and using a cohort with normal (equal) version.

Lastly, the addition of a biopsychosocial questionnaire to a study's participant questionnaire, for example the Start back screening tool (O'Keeffe et al., 2018), could be beneficial in identifying "high risk" participants. Its inclusion in a study's prospective participant recruitment process may enhance a group's final composition, refining the research.

7.4 Strengths and Limitations

7.4.1 Strengths

A strength of this research was that it validated a unique and precise tool for use in hip range assessment. The IMU enables ease of use, allowing assessment with less manpower. The sensor also permitted the distinctive measurement of hip rotation in 30^o of hip flexion, furthering the study of combined hip movements.

As previously mentioned this is the first time to the author's knowledge that hip rotation ROM has been assessed in the 30^o supine position. Its range restrictions offer insight into lumbar mechanisms of injury. Furthermore, this range appears to be more sensitive than the prone or sitting position in identifying the prescence of dominance influenced, weight-shifted standing posture's effects on hip range. This in turn assists in the clinical identification of malrotated and side-bent spines. Treatment of these lumbar and hip disorders helps the clinician manage their associated symptoms.

Identification and validation of the left AIC pattern is also a unique feature of this research, although the results would have had greater sway had the analyses incorporated the influence of leg dominance. This was made possible through measurement of all hip ROMs, allowing for a wider ranging analyses and hip pattern recognition. This opportunistic finding should receive greater attention in the future. It highlights the potential of accurate, objective hip ROM examination in the diagnosis of hip pathologies but also gives the clinician a global view of the patient's condition.

A benefit of passive rather than active hip range testing, is that the joint range outcomes are unencumbered by the participant's muscle strength. It is not unusual for muscle weakness to limit an active ROM, while the joint's passive range remains unaffected. Although neurological fallout was an exclusion, passive testing highlighted any unrecognised joint stiffness present in the groups.

7.4.1 Limitations

7.4.1.1 Limitations Caused by Soft Tissue Artefact

Although uniform across the experimental and control groups, soft tissue artefact would have had some influence on the outcome of hip range values through its effects on IMU placement. Audenaert et al., (2011) using elecromagnetic sensors, tracked the movements of transosseous screws and an orthosis fixed to a cadaver's skin during different hip motions. They found an average difference between the skeletal and skin sensors of 3.2^{o} at the femur and 1.8^{o} at the pelvis at the end of range. This limitation is common in ROM studies as the alternative, inserting a pin into the bone, carries the risk of sepsis and has related ethical considerations.

7.4.1.2 Limitations Caused by Muscle Length

Although each participant's knee was extended during the MTT to negate the effects of rectus femoris length on the iliopsoas' length, the test should have been performed in hip abduction with knee extension (Sahrmann, 2002; Van Dillen, et al., 2000). This would have also cancelled the influence of tensor fascia lata tightness on the final iliopsoas length measurements. This limitation has a bearing on the accuracy of the study's iliopsoas and SLR length measurements. It also consequently undermines the outcomes used for the hip extension ROM and iliopsoas length comparative analysis in Appendix I. However, in the author's opinion, it did not have an impact on objective five's results. As active lumbar extension is performed with hips in neutral abduction/adduction, it follows that the MTT should have been measured in the same position. Appropriately, the method used to measure hip flexor length in this study mirror the anatomical structures that limit active lumbar extension in the standing position. Had the MTT been correctly performed to establish the iliopsoii's length, namely, with the hip in abduction, active lumbar extension should have also then been performed in bilateral hip abduction to ensure that the iliopsoii were the range limiting and potential (lumbar) symptom generating muscle - instead of the tensor fascia lata. Future research would do well to recognise this distinction.

The participant's rectus femoris length was not determined beforehand. Following Peterson Kendall et al. (1993), a rectus femoris muscle of normal length, placed in the Thomas Test position, would extend 10^o over the hip and allow 80^o of knee flexion, achieving a combined range of 90^o. Therefore theoretically, bending the knee to 90^o in the prone position, (with a rectus femoris of a normal length) places a stretch on this muscle, positioning the pelvis in neutral tilt. A short rectus femoris (and/or tensor fasia lata) pulls the pelvis into an anterior tilt. This may create some slack in the Iliofemoral ligament, increasing ER in this position. The anterior pelvic tilt could also alter the orientation of the acetabulum, potentially reducing hip flexion and IR range (see section 7.4.1.4 below). Similarly, short rectus femorii could have also affected the outcomes of the different sagittal plane position's effects on hip rotation ROM and in the event of a muscle length assymmetry, side-to side prone rotation comparisons.

7.4.1.3 Limitations Caused by Tibiofemoral Position and Flexibility

The tibiofemoral joint's valgus or varus angle was not measured nor factored into the hip rotation calculations. Placing a valgus knee's shin in the vertical starting position, may externally rotate the hip, diminishing the ER range and increasing the IR range. Similarly, positioning a varus knee's shin in the vertical, may internally rotate the hip, diminishing the IR range and increasing the ER range. It is possible that placing the knee in a 90^{o} position eliminates this effect, but to the author's knowledge, no research investigating the influence of genu valgum/varum on hip rotation exists.

Similarly, the tibiofemoral joint's flexibility was not accounted for in the hip rotation calculations. There was no option but to make use of the tibia to measure hip rotation so this circumstance could not be averted. Foregoing the tibial tuberosity and following Clarkson's (2013) method of using the midpoint of the patella as the axis point also presented its own complications. This would have required overcoming the challenge of identifying the patella's borders in knee flexion and linking this mid-point with the mid-malleolar point - plotting an axis on the shin over the protruding tibial tuberosity. On completion of the main study, a paper was uncovered that had investigated this concern. Harris-Hayes et al., (2007) found that female's with immobilised tibiofemoral joints showed significantly lower (prone) hip rotation range, than when the knee was not stabilised. Men exhibited no difference between the two conditions. The similar group gender ratios in this research, may have negated this limitation to some extent (see Table 5.1). However, these hurdles could have affected the hip rotation's values and possibly the side-to-side range comparison's results, although the problem would have extended across both groups.

7.4.1.4 General Limitations

The cohort selected for this study focused on persons with chronic non-specific lower back pain. Individuals with neurological problems, acute conditions and spinal instabilities were excluded. The hip measurements obtained reflect and may be characteristic of this population, conceivably they may not be generalisable to people with other diagnoses. It is possible, that limited hip ROM predisposes affected persons to disc injury and skeletal instabilities. This is a topic for future research.

Another potential limitation of this study was the omission of a questionnaire to screen and identify individuals psychosocially "high risk" (Traeger and McAuley, 2013). As discussed in section 6.3 above, excluding these individuals from the pain group would have enhanced its composition. None of the lumbar pain participants appeared overly anxious nor displayed noteable fear-avoidance behaviour, but not having employed a sensitive tool to recognise these features, they may have been missed.

Although all volunteers who had received any form of hip treatment in the previous six months were excluded, participants who qualified for the lumbar pain group were not questioned on whether any lumbar treatment or exercises they had received, could have potentially affected their hip ROM. This oversight could have influenced this group's hip range results.

An added limitation related to the age of the pilot study participants. The original research methodology demanded the assessment of hockey players 18 years and older. The pilot study commenced using this cohort. As insufficient players volunteered for the research, the study population was amended, utilising people over the age of 40. Consequently, eight hockey players of the eventual 11 pilot participants had already been assessed. The researcher did not think it was necessary to start the pilot study afresh as the procedural problems had already been identified (through the testing of these younger volunteers) and he did not want to forgo these studies because of the difficulties attracting participants. As a result, only three pilot study participants were over the age of 40. Ideally the pilot and main study's population should have comprised the same aged people - this lack of consistency was another limitation of this research project.

Small sample sizes were an additional limitation. The splitting of the two groups into their smaller subgroups for the association of hip range and lower back symptoms analyses, reduced certain test's statistical power. Making use an alpha of 5%, this research's statisical power was estimated at 76.3%. This was slightly lower than the conventionally accepted power of 80% (Van Dillen et al., 2008).

An unavoidable limitation was the potential effect that furnishings and building material's ferromagnetic properties had on the accuracy of the IMU. As previously mentioned, iron objects within one metre of an electromagnetic sensor are thought to affect its functionality (Audenaert et al., 2011). All the participant testing was conducted on wooden furniture, however a second metal plinth was approximately one metre away. The validation studies were conducted on wooden and granite benchtops 80cm above a steel reinforced concrete floor, with metal window frames also approximately one metre away. Although it is uncertain whats effects these objects had, the IMU performed well in this environment, outlined earlier in the validation studies.

A limitation of the study's passive hip ROM testing was the potential fatigue of the researcher. This could have had an effect on the outcomes. Although most participants were assessed late morning when the examiner was rested and only one volunteer was assessed each day, a one and a half hour testing procedure can take its toll.

This study focused on hip range's effects on lumbar symptoms. Although beyond the scope of this research, general strength and strength imbalances could have had a bearing on lumbar symptom provocation during the objective lumbar movement testing. This is illustrated by the notion that different pelvic tilt positions can affect the acetabulum's orientation and thereby influence hip range (Pierannunzii, 2017). Drawing on three-dimensional hip modelling and radiological studies, anterior pelvic tilt was shown to cause acetabular retroversion resulting in reduced hip flexion and IR ROM (Ross et al., 2014; Patel et al., 2019; Henebry and Gaskill, 2013). Not without its controversy, certain authors are of the opinion that anterior pelvic tilt causes an increase in acetabular anteversion (Babisch et al., 2008). Studies researching the effects of acetabular osteotomy on pelvic tilt, found that no relationship existed between pelvic tilt and acetabular orientation (Grammatopoulos et al., 2020; Roussot et al., 2021). However, it should be noted that in both Grammatopoulos et al's. (2020) and Roussot et al's. (2021) studies, participants were evaluated with supine radiographs. This could be of concern as pelvic tilt has been shown to vary significantly between the supine and standing positions (Babisch et al., 2008; Roussot et al., 2021) - supine imaging has been criticised for not reproducing the functional, weight-bearing relationship between acetabulum and femur (Henebry and Gaskill, 2013). This demonstrates that hip ROM, measured in supine in this study and thought to be the physiological lumbar movement's limiting factor, may have been altered by muscle strength (for example, that of the lower abdominals) in the weight-bearing position. This limits conclusions drawn on the effect of hip ROM on lumbar symptom provocation. Future research should examine hip and lumbar ROM and muscle strength to determine any relationship.

Lastly, although shedding light on left AIC presentation and its potential propogation of lower back pain, the addition of leg dominance and its inclusion in the statistical analyses would have enhanced these results. This could be corrected in the future using this study's data, but should also be a consideration of prospective research elucidating the condition and its effects.

7.4.1.5 IMU Placement Limitations

The IMU's great sensitivity necessitated precise placement. For the sagittal plane's measurements this proved to be a particular challenge. Initially, historical and palpably prominent, anatomical landmarks were selected (Clarkson, 2000; Roach, San Juan, Suprak and Lyda, 2013; Roach et al., 2015; Gugliotti et al., 2018; Nussbaumer et al., 2010; Beneck et al., 2018; Malliaras et al., 2009; Van Dillen et al., 2008; Kouyoumdjian et al., 2011). Conventional methodology, makes use of the greater trochanter and lateral epicondyle. The intention was to place the IMU on the mid-point of the line joining these two loci. Identifying and marking these two landmarks for reproduction from person to person and mirroring that side-to-side proved difficult. The lateral epicondyle is an easy locatable, superficial point but the greater trochanter is deep under the skin and has a relatively large surface area. A surprising omission in all other studies' methodology, has been a discussion on how they identified the greater trochanter's midpoint. This presented a considerable challenge in this study and must surely be the case in earlier research. It may be possibly alluded to in 10º margins of error, but is never directly addressed (Ellison et al., 1990; Ellenbecker et al., 2007; Moreno-Perez et al., 2016). Selecting what seemed to be the same prominence over the greater trochanter on the left and right sides in one instance during hip flexion pilot testing, resulted in a 5º starting position side discrepancy. This difference could be significant when measuring hip extension range for example, which some researchers (Peterson Kendall et al., 1993; Sahrmann, 2002; Roaas and Andersson, 1982) believe to be as little as 10º. Using the greater trochanter's bisected mid-point did not provide the answer either, as soft tissue artefact and palpation through substantial layers of muscle caused considerable shift of marked points on release of the tissue.

As the study's objectives required the same starting point on each side and across participants in both groups, in the pursuit of greater accuracy it was deemed more suitable to disregard the greater trochanter and lateral epicondyle and rather use the sensor's spirit level to ensure consistent and precise IMU placement. The IMU was positioned and then taped to the lateral thigh when its spirit level function displayed a 0º reading. With the sensor in the level position, it was calibrated and measurements taken from this starting point. Although this negated the above mentioned problems, it also distorted the sagittal plane measurements. This is outlined through experiments in Appendices G, H and I.

7.4.1.6 Limitations Identifying Sagittal Plane Neutral

Finding the sagittal plane ranges', neutral (0^o degree), starting position also proved to be a challenge. In supine, the greater trochanter rests at a greater height off the plinth than the lateral epicondyle, this results in the hip starting in a slightly extended position when testing hip flexion. In fact, as the femoral neck is angled anteriorly and medially (Kapandji, 2011), the hip's true axis of rotation is still slightly higher off the bed's surface, increasing this starting angle. When in prone, the larger pelvis places the hip in a slightly flexed position during hip extension testing. Another consideration, is the weight of an individual's pelvis, which depending on the plinth's cushioning, would also alter the angle between the pelvis and the lighter knee. Identification and offset of these starting position extension and flexion angles, would result in precise final measurement of these ranges. Since this was not possible, sagittal plane ranges are somewhat exaggerated or undervalued in this study.

An alternative means of finding hip joint neutral, negating the use of the greater trochanter and rather using the lateral epicondyle exclusively, would be of benefit. The author found a unique solution, but it unfortunately proved impractical. Its rationale is discussed in greater detail in Appendix J below.

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Appendix A

Thompson’s Disc Degeneration Classification System (Tanaka et al., 2001)

The MRI categories, using T2-weighted midsagittal images, are only listed below, as this would solely be available in a clinical setting:

Grade I is characterised by a distinctly demarcated, homogenous bright nucleus and dark grey annulus; endplates which appears as a single dark line and vertebral bodies with rounded margins.

Grade II has dark bands extending across the annulus fibrosis; the endplate seeing an increased central concavity with tapering margins of the vertebral body.

Grade III is defined by an unclear distinction between the annulus and nucleus which is grey tone with dark and bright specks; the endplate line less definite with projections from the vertebral body margins.

Grade IV is described with an indistinguishable annulus and nucleus comprising enlarging dark and bright areas and a reduced grey region. Focal defects appear in the endplate line with osteophytic projections less than 2 mm off the vertebral body.

Finally, Grade V has a collapsed disc space where bright and dark signals predominate. Nucleus pulposus and annulus fibrosis signals are contiguous, with a thickened and irregular endplate and vertebral body margin osteophytes that are greater than 2mm.

Appendix B

Ethics Certificates

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

R14/49 Mr Kevin Ermann

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

CLEARANCE CERTIFICATE NO. M181041

NAME: (Principal Investigator)	Mr Kevin Ermann
DEPARTMENT:	Physiotherapy 44 Ashford Rd, Parkwood, Johannesburg
PROJECT TITLE:	The effects of asymptomatic hip hypomobility and hypermobility on lumbar symptoms in hockey players
DATE CONSIDERED:	26/10/2018
DECISION:	Approved unconditionally
CONDITIONS:	
SUPERVISOR:	Benita Olivier
APPROVED BY:	Dr CB Penny, Chairperson, HREC (Medical)
DATE OF APPROVAL:	05/12/2018

This clearance certificate is valid for 5 years from date of approval. Extension may be applied for.

DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Research Office Secretary on the Third Floor, Faculty of Health Sciences, Phillip Tobias Building, 29 Princess of Wales Terrace, Parktown, 2193, University of the Witwatersrand. I/we fully understand the conditions under which I am/we are authorized to carry out the above-mentioned research and I/we undertake to ensure compliance with these conditions. Should any departure be contemplated, from the research protocol as approved, I/we undertake to resubmit the application to the Committee. **I agree to submit a yearly progress report**. The date for annual re-certification will be one year after the date of convened meeting where the study was initially reviewed. In this case, the study was initially reviewed in **October** and will therefore be due in the month of **October** each year. Unreported changes to the application may invalidate the clearance given by the HREC (Medical).

Principal Investigator Signature

Date 15/12/2018

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

04 November 2019

Mr Kevin Ermann
Physiotherapy

Sent by email to: kermann@tiscali.co.za

Re: **Study no: M181041**
Study Title: The effects of asymptomatic hip hypomobility and hypermobility on lumbar symptoms in hockey players
Principal Investigator: Mr Kevin Ermann
Protocol Amendments

This letter serves to confirm that the Chairman of the Human Research Ethics Committee (Medical) has approved protocol amendments as detailed in your letter dated 03 October 2019. The following documents were received:

- Request to include physiotherapy and occupational therapy students in the study.
- Information sheet
- Permission from the university registrar

Thank you for keeping us informed and updated.

UNIVERSITY OF THE WITWATERSRAND
OFFICE OF THE DEPUTY VICE CHANCELLOR RESEARCH
04 NOV 2019
RESEARCH OFFICE
JOHANNESBURG

Yours Sincerely,

....

Ms Zanele Ndlovu
Administrative Officer
Human Research Ethics Committee (Medical)

Research Office Secretariat: Faculty of Health Sciences, Phillip Tobias Building, 3rd Floor, Office 301, 29 Princess of Wales Terrace, Parktown, 2193 Tel +27 (0)11-717-1252 /1234/2656/2700 Private Bag 3, Wits 2050 email: zanele.ndlovu@wits.ac.za Office email: hrec-medicalresearchoffice@wits.ac.za Website:

UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

OFFICE OF THE DEPUTY REGISTRAR

18 September 2019

Kevin Ermann
Student number 9100943V
Masters Degree by Dissertation
School of Physiotherapy

TO WHOM IT MAY CONCERN

"The effects of asymptomatic hip hypomobility and hypermobility on lumbar symptoms in hockey players"

This letter serves to confirm that the above project has received permission to be conducted on University premises, and/or involving staff and/or students of the University as research participants. In undertaking this research, you agree to abide by all University regulations for conducting research on campus and to respect participants' rights to withdraw from participation at any time.

If you are conducting research on certain student cohorts, year groups or courses within specific Schools and within the teaching term, permission must be sought from Heads of School or individual academics.

Ethical clearance has been obtained. (Protocol Number: M181041)

Nicoleen Potgieter
University Deputy Registrar

Private Bag 3, Wits, 2050, South Africa | T +27 11 717 1204/8 | F +27 86 553 2271 | www.wits.ac.za

Department of Physiotherapy

Faculty of Health Sciences, Department of Physiotherapy · Private Bag 3, Wits, 2050, South Africa
Tel: +27 11 717 72015/3702 · Fax : 27 86 5534 762 · E-mail: Veronica.Ntsiea@wits.ac.za · www.wits.ac.za

WITS UNIVERSITY

16 September 2019

The Chair
Research Ethics Committee
Faculty of Health Sciences
University of Witwatersrand

Permission to conduct research within the Physiotherapy Department

This serves to confirm that I am supportive of Mr Kevin Ermann's research project and give him permission to use the physiotherapy department as a recruitment base for his study that requires participation of physiotherapy students.

The study involves assessment of physical activity, hip range of movement, flexibility and lumbar range of movement. Permission to recruit the physiotherapy students is granted with the understanding that the students will be given an opportunity to provide informed consent to participate in the study and they will be made aware that participation in this study is voluntary.

Regards

Ntsiea

Associate Professor Veronica Ntsiea
Head of Physiotherapy Department
School of Therapeutic Sciences

THERAPEUTIC Sciences

Occupational Therapy

School of Therapeutic Sciences • Faculty of Health Sciences • 7 York Road, Parktown 2193, South Africa
Tel: +27 11 717-3701 • Fax: +27 11 717-3709 • E-mail: denise.franzsen@wits.ac.za

Kevin Ermann 30/09/2019

Research title: The effects of asymptomatic hip hypermobility on lumbar symptoms in hockey players.

Dear Kevin

Re: permission for Occupational Therapy students to participate in research

I hereby grant permission for you to approach Occupational Therapy students to invite them to participate in your research. It goes without saying that they cannot miss class time or fieldwork to participate.

Regards,

Dr Adams
HOD
Occupational Therapy Department

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

03 February 2020

Mr Kevin Ermann
Physiotherapy
44 Ashford Rd
Parkwood

Sent by email to: kermann@isicali.co.za

Re: **Study no:** M181041

Project Title: The effects of asymptomatic hip hypomobility and hypermobility on lumbar symptoms in hockey players (request title change – The association between hip hypomobility and hypermobility, and lumbar symptoms in adults aged 40 years and older)

Principal Investigator: Mr Kevin Ermann

Protocol Amendment

This letter serves to confirm that the Chairman of the Human Research Ethics Committee (Medical) has approved protocol amendments as detailed in your letter dated 21 November 2019.

Thank you for keeping us informed and updated.

Yours Sincerely,

UNIVERSITY OF THE WITWATERSRAND
OFFICE OF THE DEPUTY VICE CHANCELLOR RESEARCH
03 FEB 2020
RESEARCH OFFICE
HREC (Medical)
JOHANNESBURG

....

Ms Zanele Ndlovu
Administrative Officer
Human Research Ethics Committee (Medical)

Research Office Secretariat: Faculty of Health Sciences, Phillip Tobias Building, 3rd Floor, Office 301, 29 Princess of Wales Terrace, Parktown, 2193. Tel: +27 (0)11-717-1252/1234/2656/2700. Private Bag 3, Wits 2050, email: [illegible] Office email: [illegible]@wits.ac.za Website: [illegible]

Appendix C

Information sheet for prospective participants

Study Title: The association between hip hypomobility and hypermobility, and lumbar symptoms in adults aged 40 years and older.

Dear Sir/Madam,

I'm a physiotherapist conducting research for a Master's degree through the physiotherapy department at the University of the Witwatersrand. I would herewith like to invite you to participate in this study.

My research is looking into the relationship that hips have with the lumbar spine. More specifically, I'll be researching whether stiff or hypermobile hips are linked to back pain. Hip stiffness/hypermobility could result in compensations in the lower back, resulting in muscle, intervertebral disc and lumbar joint strain.

Who is eligible for the research study?

I am seeking adult men and women, 40 years of age and older for this research. <u>I'd be looking for individuals with and without long-term lower back pain, who currently don't have any hip problems.</u>

What does the research procedure entail?

Participants will be required to complete a few forms. Their height, weight, joint laxity, hip joint range and (those with back pain) lumbar movements will be assessed.

Questionnaires will be emailed to prospective participants to determine whether or not they are eligible for the study. The initial emailed questionnaire will take 5 minutes to complete and then 3 minutes for a second questionnaire on the day of testing. The information collected would pertain to their musculoskeletal history, and their typical daily and sporting activity levels.

The principal researcher would be measuring every participant's hip ROM. Measurements are to be made with an IMU (a 5cm square rubber encased sensor) and with a goniometer (which looks like a protractor with moveable arms). The sensor would be secured to the skin using strapping. The instrument will be placed on the side of your mid-thigh, just above the front of the knee and ankle. The goniometer will be placed over the frontal prominences of the pelvis (at the waist line). These measurements will take place in lying on back and stomach, with legs placed on a 30° angled framework and in sitting. Participants will be required to wear loose fitting shorts. A few ink markings will be made on the individuals' legs. Study participants with back pain will also be required to move through general ROM to the onset of pain or end of range (whichever comes first). Your ligament laxity will also be quickly assessed. This involves actively moving thumb, little finger, elbows and knees into certain positions and then seeing how far you can bend forwards- these tests should be pain-free.

All testing will take approximately 90 minutes. Participants are to be assessed at my practice rooms in Rosebank, Johannesburg.

What would be the benefits from participating in the study?

Participants would get a greater understanding of their back and lower limb biomechanics. A stiff/hypermobile hip impacts on the local musculature and soft tissues but also affects the lower back, knee and ankle. Participants would be made aware of any findings and given some advice on how to correct these problems. This in turn would potentially assist in the treatment of any existing conditions, improve sporting performance, enhance daily movement and reduce the risk of injury. Information gleaned from the research may be of help to physiotherapists taking care of patients with similar problems in the future.

What are the risks in participating in the research?

A participants' hips will be moved passively (i.e. by the researcher) through to its end of range. This would purposefully place some stretch on the joint's ligaments. A hip joint problem might elicit minor pain. As all participants wouldn't have a history of hip problems and since the movement will be performed in a slow, gentle manner, no ill effect is anticipated.

Compensatory movement may occur in the lumbar spine when an individual's hips are moved. This may reproduce back pain in those with the condition. Once again, as the hip passive movement is never "forced" and will be immediately stopped should pain be elicited; since the pelvis is to be secured manually or with belts preventing lumbar movement and since people with serious back problems are excluded from the study (through the questionnaires), here too no ill effect is anticipated. As all lower back movements will be controlled and actively performed by the participant who will be instructed to stop at the onset of any symptoms (or end of the movement), the study shouldn't have any harmful and lasting effect on a lumbar condition. Ligament laxity testing will be performed by the participant themselves so no ill effect is expected.

Participation

Participation is voluntary. The participant can withdraw from the study at any time, without any reason necessary. In this event, any information collected would be destroyed. There is no payment for participation.

Confidentiality

All personal information will be treated in the strictest confidence and will be only available to the principal researcher and his supervisor. Should you agree to the research, you'll then be allocated a case number providing anonymity. This number would solely appear on forthcoming questionnaires (to determine your eligibility and to exclude individuals with serious conditions). All documentation would be emailed to you beforehand to avoid unnecessary travel. Only the principle researcher will have your full name and contact details. Any medical information collected will be securely stored. All information collected during the course of the study will only be used for these purposes and will not be disseminated any further.

This study has been approved by the Human Research Ethics Committee (Medical) of the University of the Witwatersrand, Johannesburg ("Committee"). A principal function of this Committee is to safeguard the rights and dignity of all human subjects who agree to participate in a research project and the integrity of the research. If you have any concern over the way the study is being conducted, please contact the Chairperson of this Committee who is Professor Clement Penny, who may be contacted on telephone number 011 717 2301, or by e-mail on Clement.Penny@wits.ac.za. The telephone numbers for the Committee secretariat are 011 717 2700/1234 and the e-mail addresses are Zanele.Ndlovu@wits.ac.za and Rhulani.Mukansi@wits.ac.za

If you have any enquiries please contact me on 082-927-1990 or via email at kermann@tiscali.co.za . Should you want to enrol in the study, please complete the attached "Informed consent form" and email that back to me. I will contact you thereafter.

Kind regards,

Kevin Ermann

Physiotherapist

Appendix D

Participant Questionnaire

Section A:

Date: ___________ Study number (for office use only): _______________

Age: ___________ Gender: _________

Please complete the following questions:

Are you able to lie on your stomach?

Yes/ No

If you answered "No" to the above question you don't need to continue with the questionnaire. Thank you for your time and assistance.

	Yes	**No**
Have you ever received surgical treatment for a lower back condition?		
Do you currently have pain, numbness and/or pins & needles down either leg?		
Do you currently have numbness in your groin?		
Do you currently have problems controlling your bladder or bowel?		
Do you have a **true** leg length discrepancy? Is one leg 2cm or longer than the other leg?		
As an infant, did you have a congenital hip problem?		
Have you ever experienced hip injury or trauma that required surgical treatment?		
Have you ever experienced a knee injury or trauma that required surgical treatment? Have you had a total knee replacement?		
Do you have a **chronic** symptomatic knee problem?		

If applicable, are you pregnant?		
Are you currently or have you taken steroids for a prolonged period of time?		

Have you ever been diagnosed with or currently have any of the following conditions?

	Yes	**No**
• Spinal conditions eg. tumours or infections		
• Marked spinal curvature eg. kyphosis or scoliosis		
• Spondylolisthesis, spondylolysis or anterolisthesis		
• Spinal stenosis		
• Spinal instability		
• Spinal, pelvis, coccyx or hip fracture		
• Ankylosing spondylitis		
	Yes	**No**
• **Acute or sub-acute** lumbar disc herniation		
• Lower limb impairment eg. surgery		
• Any form of unresolved cancer		
• Osteoporosis (those with **high risk** of fracture)		
• Have you ever been diagnosed with a systemic (across the whole body) inflammatory condition? Eg. Rheumatoid arthritis		

1. Do you currently have pain in the groin, side of the hip, thigh or butt? Y/ N

2. Are you receiving or have received physiotherapy, chiropractic, osteopathic, and/or biokinetics treatment within the last six months for a <u>hip condition</u> (that would be for pain experienced in the groin, side of the hip, thigh or butt)? Y/ N

3. Are you regularly (two or more times per week) using anti-inflammatories or painkillers for a hip condition (that would be for pain experienced in the groin, side of the hip, thigh or butt)? Y/ N

4. Do you have recurrent lower back pain **or** chronic lower back pain ?

Recurrent lower back pain is defined as symptoms present on less than half the number of days in a 12-month period, occurring in multiple episodes over the year. **Chronic lower back pain is defined** as symptoms present on greater than half the days in a 12-month period, occurring in a single or in multiple episodes ? Y / N

If Yes, please continue to "Section B" below; if "No" please continue with the questionnaire.

5. Have you experienced lower back pain for longer than two weeks in the past year? Y / N

6. Are you receiving or have received physiotherapy, chiropractic, osteopathic and/or biokinetics treatment within the last six months for a lower back problem? Y / N
7. Are you regularly using anti-inflammatories or painkillers (two or more times per week) for a lower back problem? Y/ N

Section B:

Weight: ______________ Height: _________________

Thank you for completing these questionnaires. Please email these to kermann@tiscali.co.za . If you're eligible for the study, you will be contacted in due course.

Kindly note: It is of great importance that you refrain from any stretching, warm-up exercises or sport prior to the assessment on the day of testing. The reason being, is that it would have a major impact on the accuracy of the study. Secondly, please don't apply moisturiser to your legs on the day of the assessment - I won't be able to tape the sensor to your skin.

If you are accepted for participation in the study and you take anti-inflammatories or pain-killers for any condition, please draw this to our attention during scheduling of your appointment.

Thanking you in anticipation.

Appendix E

Informed Consent Form

I, the undersigned, hereby confirm that I understand and agree to participate in the proposed research as outlined in the supplied communique. I acknowledge that I'm 18 years of age or older. I agree to complete the required questionnaires. I understand that my personal details and any medical information will be securely stored and only be known to the principal researcher and his supervisor. I understand that my confidentiality will be protected at all costs, but that absolute confidentiality cannot be guaranteed. I understand the nature, benefits and risks of the research. I had sufficient opportunity to consider whether I want to proceed with the study. I realise that the researcher will need to uncover, mark and measure specific parts of my body. It is further known to me that I can withdraw this consent and from the study at any time. I acknowledge that my personal and medical information will be destroyed if I withdraw from the research study. I understand that there is no remuneration for the study and that participation is voluntary.

I hereby accept and agree to the terms and conditions mentioned above.

Full Name: ____

Contact phone number: ______________________________________

Email address: ____

Signature: ____

Date: ____

Place: ____

For office use only:

Study number: ____________________

Appendix F

Validation Study Results

Table F 1 Validation Study 4 Results (20 Oscillations)

Aim: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the frontal plane.

After calibration, the sensor was moved 10 times in a clockwise and anti-clockwise direction, through its starting point 20 times, to the 70º points. The goniometer's mobile arm's position and the corresponding IMU application's reading is tabulated below. Values below are in degrees. The results below are stated in chronological order.

Goniometer Position:	IMU Application Reading:
Start position: 0	0
Clockwise 10	10
Clockwise 25	25
Clockwise 40	40
Clockwise 50	50
Clockwise 60	61
Clockwise 70	71
Anti-clockwise 20	19
Anti-clockwise 60	55
Anti-clockwise 70	65
Anti-clockwise 30	24
Anti-clockwise 10	4

Table F 2 Validation Study 4 Results (10 Oscillations)

Aim: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the frontal plane.

The same test was then repeated, the sensor was calibrated but moved through the starting point 10 times, namely 5 times in each direction. It was moved through the 0^{o} starting point, to the clockwise and anti-clockwise 70^{o} points. The goniometer's mobile arm's position and the corresponding IMU application's reading is tabulated below. Values below are in degrees.

Goniometer Position:	IMU Application Reading:
Start position: 0	0
Clockwise 20	21
Clockwise 30	31
Clockwise 40	41
Clockwise 50	51
Clockwise 60	60
Clockwise 70	71
Anti-clockwise 10	9
Anti-clockwise 20	20
Anti-clockwise 30	30
Anti-clockwise 40	41
Anti-clockwise 50	50
Anti-clockwise 60	60
Anti-clockwise 70	69
End position: 0	3

Table F 3 Validation Study 5 Results (First Test)

Aim: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the sagittal plane in the upright position.

IMU calibrated at the goniometer's 0^o position. IMU and goniometer then moved 10 times from 0^o to 160^o positions. The goniometer's mobile arm's position and the corresponding IMU application's reading is tabulated below. Values below are in degrees.

Goniometer Position:	IMU Application Reading:
Start position: 0	0
10	10
20	21
30	31
40	41
50	51
60	61
70	71
80	81
90	91
100	101
110	111
120	121
130	130
140	140
150	149
160	159

Table F 4 Validation Study 6 Results

Aim: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the sagittal plane in the inverted position.

IMU calibrated at the goniometer's 0^o position. IMU and goniometer then moved 10 times from 0^o to 60^o positions. The goniometer's mobile arm's position and the corresponding IMU application's reading is tabulated below. Values below are in degrees.

Goniometer Position:	IMU Application Reading:
Start position: 0	0
10	9
20	19
30	28
40	38
50	48
60	57
End position: 0	1

Table F 5 Validation Study 7 Results

Aim: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the transverse plane through the "u" arc of motion in the upright position.

IMU calibrated at the goniometer's 0º position. IMU and goniometer then moved 10 times (5 times in each direction through the 0º mark) from 0º to 80º positions. The goniometer's mobile arm's position and the corresponding IMU application's reading is tabulated below. Values below are in degrees.

Goniometer Position:	IMU Application Reading:
Start position: 0	0
Clockwise 10	10
Clockwise 20	21
Clockwise 30	31
Clockwise 40	41
Clockwise 50	51
Clockwise 60	61
Clockwise 70	71
Clockwise 80	81
End position: 0	1
Anti-clockwise 10	10
Anti-clockwise 20	20
Anti-clockwise 30	30
Anti-clockwise 40	41
Anti-clockwise 50	51
Anti-clockwise 60	61
Anti-clockwise 70	71
Anti-clockwise 80	82
End position: 0	1

Table F 6 Validation Study 8 Results

Aim: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the transverse plane through the "n" arc of motion in the inverted position.

The sensor was calibrated at the 0º mark and then the goniometer's mobile arm was moved 10 times (5 times in each direction through the 0º mark) through to the 80º points. The goniometer's mobile arm's position and the corresponding IMU application's reading is tabulated below. Values below are in degrees.

Goniometer Position:	IMU Application Reading:
Start position: 0	0
Anti-clockwise 10	9
Anti-clockwise 20	19
Anti-clockwise 30	28
Anti-clockwise 40	38
Anti-clockwise 50	48
Anti-clockwise 60	57
Anti-clockwise 70	67
Anti-clockwise 80	77
End position: 0	0
Clockwise 10	9
Clockwise 20	19
Clockwise 30	29
Clockwise 40	39
Clockwise 50	49
Clockwise 60	59
Clockwise 70	69
Clockwise 80	79
End position: 0	0

Table F 7 Validation Study 9 Results

Aim: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the transverse plane through the "n" arc of motion in the upright position.

The sensor was calibrated at the 0^{o} position and the goniometer's mobile arm was then moved 10 times (5 times in each direction through the 0^{o} mark) through to the 80^{o} positions. The goniometer's mobile arm's position and the corresponding IMU application's reading is tabulated below. Values below are in degrees.

Goniometer Position:	IMU Application Reading:
Start position: 0	0
Anti-clockwise 10	10
Anti-clockwise 20	20
Anti-clockwise 30	31
Anti-clockwise 40	41
Anti-clockwise 50	51
Anti-clockwise 60	62
Anti-clockwise 70	72
Anti-clockwise 80	82
Clockwise 10	10
Clockwise 20	21
Clockwise 30	31
Clockwise 40	41
Clockwise 50	52
Clockwise 60	62
Clockwise 70	72
Clockwise 80	82
End position: 0	0

Table F 8 Validation Study 10 Results

Aim: To determine whether the IMU's angle measurement function performed accurately and experienced gyroscope drift in the 60-degree-to-the-horizontal plane through the "u" arc of motion in the upright position.

The sensor's angle measurement function was calibrated at the 0^{o} mark and then the goniometer's mobile arm was moved 10 times (5 times in each direction), through the 0^{o} mark to the 80^{o} positions. The goniometer's mobile arm's position and the corresponding IMU application's reading is tabulated below. Values below are in degrees.

Goniometer Position:	IMU Application Reading:
Start position: 0	0
Clockwise 10	10
Clockwise 20	20
Clockwise 30	31
Clockwise 40	41
Clockwise 50	51
Clockwise 60	61
Clockwise 70	71
Clockwise 80	81
End position: 0	1
Anti-clockwise 10	9
Anti-clockwise 20	20
Anti-clockwise 30	30
Anti-clockwise 40	40
Anti-clockwise 50	51
Anti-clockwise 60	61
Anti-clockwise 70	71
Anti-clockwise 80	81
End position: 0	1

Table F 9 Validation Study 11 Results

Aim: To determine whether the IMU's spirit level angle measurement function performed accurately and experienced gyroscope drift in the transverse plane, through the "u" arc of motion in the upright position.

The application's spirit level function was activated with the goniometer's mobile arm in the vertical, 0^o, position. The application displayed a 1^o reading. The mobile arm (and sensor) were then moved clockwise and anti-clockwise to the respective 90^o points, moving through the 0^o point 10 times, 5 times to each side. The goniometer's mobile arm's position and the corresponding IMU application's reading is tabulated below. Values below are in degrees.

Goniometer Position:	IMU Application Reading:
Start position: 0	1
Clockwise 10	12
Clockwise 20	22
Clockwise 30	32
Clockwise 40	42
Clockwise 50	52
Clockwise 60	62
Clockwise 70	72
Clockwise 80	82
Clockwise 90	87
Anti-clockwise 10	8
Anti-clockwise 20	19
Anti-clockwise 30	29
Anti-clockwise 40	39
Anti-clockwise 50	50
Anti-clockwise 60	60

Anti-clockwise 70	70
Anti-clockwise 80	80
Anti-clockwise 90	87
End position: 0	1

Table F 10 Validation Study 11 Results

Aim: To determine whether the IMU's spirit level angle measurement function performed accurately and experienced gyroscope drift in the transverse plane, through the "n" arc of motion in the upright position.

The sensor's spirit level function was activated with the goniometer's mobile arm in the vertical, 0^o, position. The application displayed a 0^o reading. The mobile arm (and sensor) were then moved clockwise and anti-clockwise to the 90^o points respectively, moving through the 0^o point 10 times, 5 times to each side. The goniometer's mobile arm's position and the corresponding IMU application's reading is tabulated below. Values below are in degrees.

Goniometer Position:	IMU Application Reading:
Start position: 0	0
Anti-clockwise 10	9
Anti-clockwise 20	19
Anti-clockwise 30	30
Anti-clockwise 40	40
Anti-clockwise 50	50
Anti-clockwise 60	60
Anti-clockwise 70	71
Anti-clockwise 80	81
Anti-clockwise 90	87
Clockwise 10	11
Clockwise 20	21
Clockwise 30	31
Clockwise 40	41
Clockwise 50	51
Clockwise 60	61
Clockwise 70	72

Clockwise 80	82
Clockwise 90	87
End position: 0	0

Table F 11 Validation Study 11 Results

Aim: To determine whether the IMU's spirit level angle measurement function performed accurately and experienced gyroscope drift in the 60^{O}-to-the-horizontal plane, through the "u" arc of motion in the upright position.

The IMU's spirit level was activated with the goniometer's mobile arm in the vertical, 0^{o}, position - the mobile arm (and sensor) were then moved clockwise and anti-clockwise to the 90^{o} points respectively, moving through the 0^{o} point 10 times, 5 times to each side. The goniometer's mobile arm's position and the corresponding IMU application's reading is tabulated below. Values below are in degrees.

Goniometer Position:	IMU Application Reading:
Start position: 0	1
Clockwise 10	10
Clockwise 20	19
Clockwise 30	28
Clockwise 40	36
Clockwise 50	44
Clockwise 60	50
Clockwise 70	56
Clockwise 80	60
Clockwise 90	61
Anti-clockwise 10	7
Anti-clockwise 20	16
Anti-clockwise 30	25
Anti-clockwise 40	33
Anti-clockwise 50	41
Anti-clockwise 60	48
Anti-clockwise 70	55
Anti-clockwise 80	59

Anti-clockwise 90	60
End position: 0	1

Table F 12 Comparative Analysis of the Three Sagittal Plane Validation Study Results Required for the Measurement of Left Hip ER and Right Hip IR

Objectives six and seven demanded the measurement of rotation in three different sagittal positions. The IMU's angle measurement was employed for this purpose. The comparison tabulated below presents the results of validation studies seven, ten and nine's clockwise readings. These validation studies were necessary for left hip ER (corresponding with right hip IR) in the sitting, supine and prone positions respectively. The second column from the right, shows the maximum difference of the measurements between each goniometric marker and the IMU, across the three sagittal plane positions. The last column on the right, displays the maximum difference of the IMU's measurements across the three sagittal plane positions.

Goniometer Position:	Study 7 IMU Application Clockwise Reading (Sitting):	Study 10 IMU Application Clockwise Reading (Supine):	Study 9 IMU Application Clockwise Reading (Prone):	Max. Difference Between Goniometer and IMU Across the 3 Positions:	Max. Difference Between IMU Readings Across the 3 Positions:
10	10	10	10	0	0
20	21	21	21	1	0
30	31	31	31	1	0
40	41	41	41	1	0
50	51	51	52	2	1
60	61	61	62	2	1
70	71	71	72	2	1
80	81	81	82	2	1

Table F 13 Analysis of the Three Sagittal Plane Validation Study Results Required for the Measurement of Right Hip ER and Left Hip IR

Objectives six and seven demanded the measurement of rotation in three different sagittal positions. The IMU's angle measurement was employed for this purpose. The comparison tabulated below presents the results of validation studies seven, ten and nine's anti-clockwise readings. These validation studies were necessary for right hip ER (corresponding with left hip IR) in the sitting, supine and prone positions respectively. The second column from the right, shows the maximum difference of the measurements between each goniometric marker and the IMU, across the three sagittal plane positions. The last column on the right, displays the maximum difference of the IMU's measurements across the three sagittal plane positions.

Goniometer Position:	Study 7 IMU Application Anti-Clockwise Reading (Sitting):	Study 10 IMU Application Anti-Clockwise Reading (Supine):	Study 9 IMU Application Anti-Clockwise Reading (Prone):	Max. Difference Between Goniometer and IMU Across the 3 Positions:	Max. Difference Between IMU Readings Across the 3 Positions:
10	10	9	10	1	1
20	20	20	20	0	0
30	30	30	31	1	1
40	41	40	41	1	1
50	51	51	51	1	0
60	61	61	62	2	1
70	71	71	72	2	1
80	82	81	82	2	1

Appendix G

Experiment to Determine Hip Flexion and SLR Range Measurement Accuracy

The following experiment was performed to establish the accuracy of the hip flexion measurements. A horizontal line was plotted on a vertical wall, confirmed with the IMU's spirit level (Fig. G1A). The goniometer was mounted on the line and taped to the wall (Fig. G1B). The images presented in this appendix are available in a higher resolution for the reader's perusal at www.dropbox.com (email/account: kermann@tiscali.co.za ; password: research123).

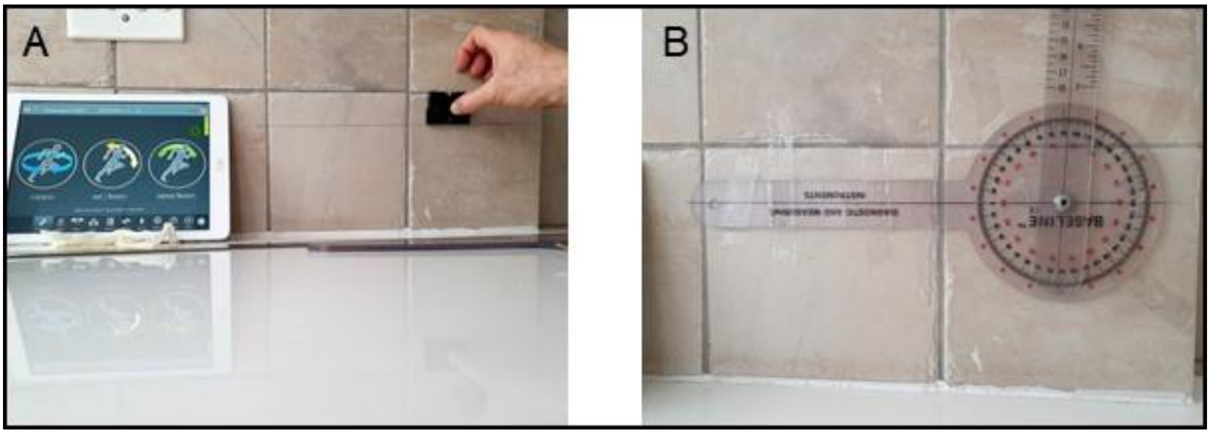

Fig. G 1 A) The application's spirit level displays 0º confirming the plotted line is horizontal. B) The goniometer's stationary arm fixed on the line.

The goniometer's mobile arm was positioned at -10º, arbitrarily selected to represent the hip extension position realised when a volunteer is placed in supine (Fig. G2A). Then as per participant testing, the sensor was mounted upright and positioned at 0º on the goniometer, through the IMU's spirit level. The sensor's flat side was against the goniometer's mobile arm (Fig. G2A). The application's angle measurement function was then calibrated (Fig. G2B).

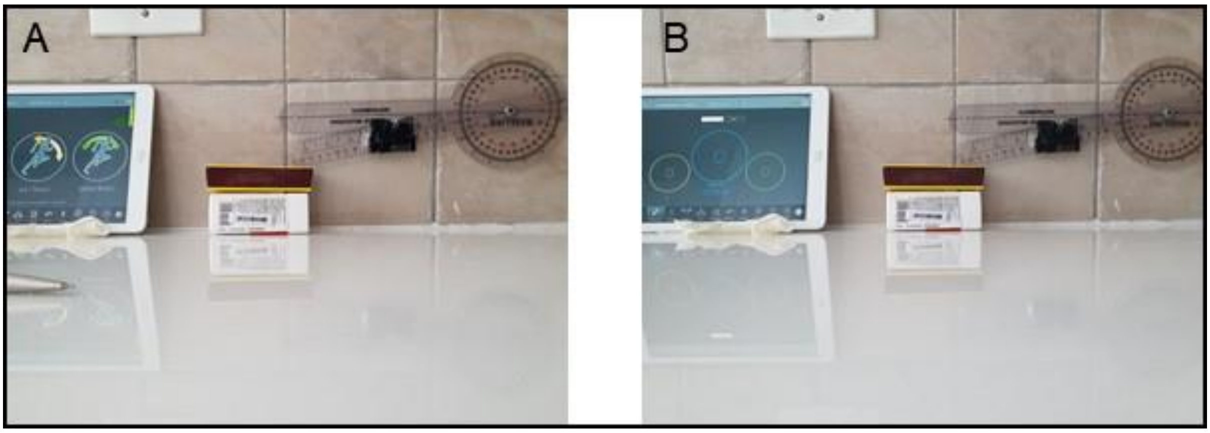

Fig. G 2 A) Goniometer's mobile arm in the -10º position with sensor attached in the horizontal position, confirmed by its spirit level. B) The IMU angle measurement function calibrated to 0º.

The mobile arm was moved to the 120º goniometer position, where the application displayed a 130º reading, as the IMU had moved through this range (Fig. G3). This demonstrated that the methodology adopted for hip flexion and SLR testing, sees an exaggerated result.

Fig. G 3 Goniometer in 120º position with application displaying 130º.

Appendix H

Experiment to Determine Hip Extension Range Measurement Accuracy

For completeness, a second experiment to assess hip extension range testing was undertaken. The goniometer was mounted on the horizontal line and the mobile arm was placed in the 10^{o} “flexion” position, simulating the conditions of extension range testing. The IMU was mounted upright on the goniometer’s mobile arm, in the perfectly horizontal position, through the spirit level function (Fig. H1A). The application’s angle measurement function was then calibrated (Fig. H1B).

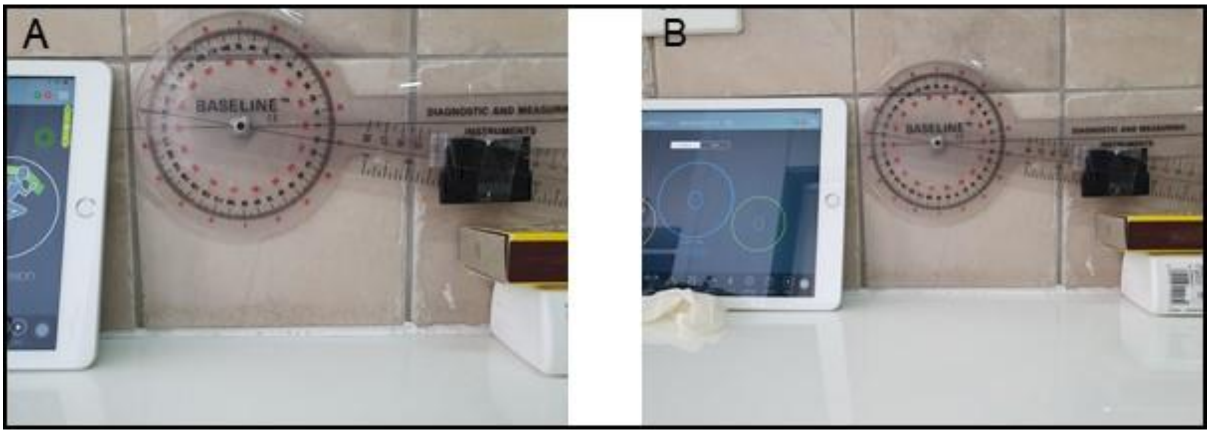

Fig. H 1 A) Horizontally mounted IMU on the goniometer’s mobile arm, positioned in 10^{o} of “flexion”. B) The application’s angle measurement function is calibrated.

The mobile arm was moved to the 30^{o} goniometer mark. Exhibiting a 41^{o} reading, this experiment demonstrated the exaggerated results in the hip extension testing outcomes (Fig. H2). The images presented in this appendix are available in a higher resolution for the reader’s perusal at www.dropbox.com (email/account: kermann@tiscali.co.za ; password: research123).

Fig. H 2 The application's angle measurement function displays 41º when the goniometer is positioned at 30º.

We can therefore conclude that the hip flexion, SLR and hip extension ranges are slightly exaggerated in the study - dependent on the unknown angle created by the difference in heights between the centre of the femoral head and lateral epicondyle above the plinth's surface.

Appendix I

Experiment to Determine MTT Range Measurement Accuracy

A final experiment replicating the MTT procedure was performed to assess the accuracy of these measurements. The goniometer was mounted on the horizontal line and the mobile arm was placed in the -10º position representing the thigh's staging position on the plinth (Fig. I1A). The IMU was mounted on the goniometer's mobile arm, in the 0º position, by means of the sensor's spirit level function (Fig. I1A). With the application's spirit level function activated, the mobile arm was moved to the goniometric 0º (Fig. I1B), 10º (Fig. I2A), -20º (Fig. I2B) and -25º positions, the application displayed 10º, 20º, -10º and -15º respectively (see Table I1 below). The images presented in this appendix are available in a higher resolution for the reader's perusal at www.dropbox.com (email/account: kermann@tiscali.co.za ; password: research123).

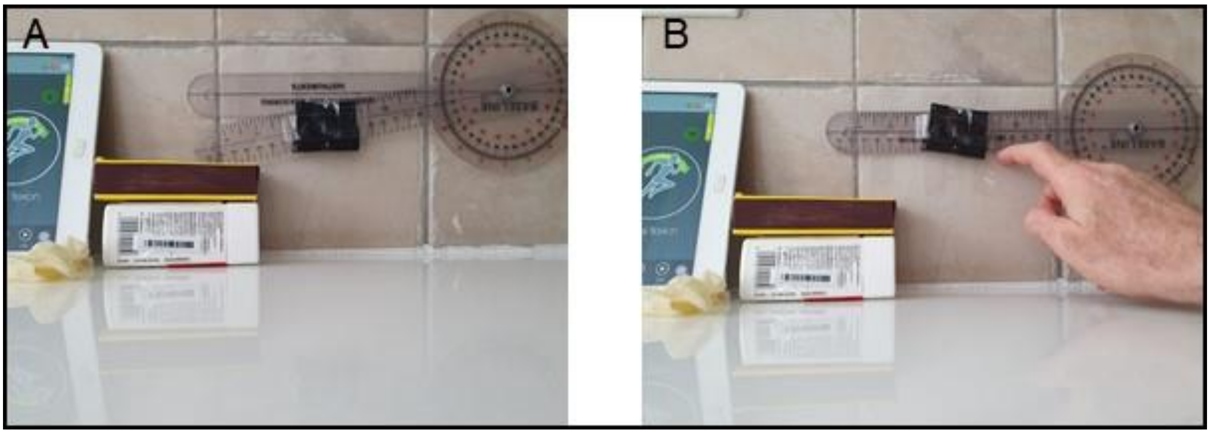

Fig. I 1 A) The staging position with goniometer at the -10º marker and IMU placed in spirit level horizontal - 0º position. B) With goniometer at 0º, the IMU's spirit level displays a 10º reading.

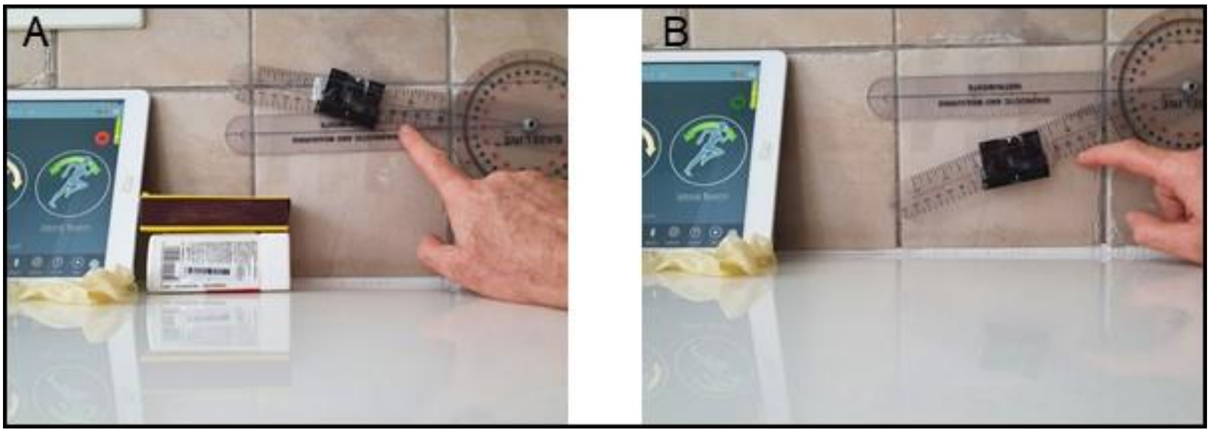

Fig. I 2 A) Goniometer in the 10° position, the application displays a 20° result. B) With goniometer at -20°, the application displays a -10° reading.

Table I 1 The Experimental Findings Showing the Discrepancies Between the Goniometer and Application's Spirit Level Readings

The goniometer's mobile arm's position and the corresponding IMU application's reading is tabulated below.

Goniometer Position:	IMU Application's Spirit Level Reading:
10	20
0	10
-10	0
-20	-10
-25	-15

These experiments help explain the language used by earlier authors (Peterson Kendall et al., 1993; Sahrmann, 2002) where without explanation, "approximate" rather than definite ranges are quoted. Arising from these experiments above and assuming a starting angle error of 10°, the study's final hip flexion average of 129.63° would be exaggerated, placing the study's true hip flexion score closer to that of other authors, approximately 120° (Clarkson, 2000; Peterson Kendall et al., 1993; Sahrmann, 2002; Roaas and Andersson, 1982). Similarly, this study's hip extension result of 32.04° is also exaggerated. Again, assuming a starting angle error of 10°, this study's corrected hip extension mean is therefore 22.04°. Positioning it midway between the proposed norms of 10° (Peterson Kendall et al., 1993; Roaas and Andersson, 1982; Sahrmann, 2002) and 30° (Clarkson, 2000).

As stated this study's SLR result of 71.00°, is somewhat at odds with earlier research documenting a low of 69.73° to a high of 88.7° in asymptomatic people (Halbertsma et al., 2001). It is however, exaggerated in the same fashion as the hip flexion range was. Again assuming a starting angle error of 10°, the corrected result would be 61.00°.

This SLR exaggeration is further compounded when adding a tight iliopsoas muscle's range to the contralateral SLR result (Peterson Kendall et al., 1993). Since the sensor and limb were not truly aligned, the study's MTT procedure misinterpreted the limb's real movement, undervaluing the MTT range's results when the limb was below the -10° starting point and exaggerating the results when the leg was above the starting point. This leads to the inaccurate addition of the iliopsoas' reduced muscle length's range to the contralateral SLR. For example, assuming a hypothetical starting degree angle error of 10°, an IMU MTT reading of two degrees suggests that the limb is two degrees above the horizontal, when in fact its true position is 8 degrees below the horizontal. These two degrees would have been added to the contralateral SLR measurement, when in fact as the limb is in reality below the horizontal, this should not have occurred. Despite this error, the short iliopsoas length compensation is likely to have had a negligle effect on the SLR average value because only five participants had a positive MTT IMU reading above one degree, ranging between 1.33° and 7.33° for the left's MTT and 1.67° and 6.67° for the right's. IMU MTT measurements of approximately >10° above the horizontal would suggest a tight iliopsoas. In this study only two individuals came close to this threshold, with ranges of 7.33° and 6.67°.

The study's final MTT mean result of -9.10º would also be undervalued by the same amount, namely by that of the starting position angle. With reference to Table I1 above, a MTT IMU measurement of -9.10º, again with the assumption of a 10º starting error, indicates that the corrected, true MTT value is approximately -19.10º. Admittedly this is a much greater range than what has been proposed in the past (see paragraph 2.7.2 above). Secondly, this study like others did not measure the lumbar spine's range contribution, but by recognising the starting position measurement faults, in the author's opinion, the result of -19.10º more accurately reflects the clinical and functional reality.

At first glance the two hip extension testing position's means, namely hip extension (32.04º) and MTT (-9.10º), appear to conflict, but on consideration of the IMU starting position and skeletal morphology's effects, the two averages are not that dissimilar. To illustrate this point, assume a starting position error of 10º, resulting in a 10º exaggeration of the hip extension range and an undervalued MTT range of 10º. Then using this study's results, that is hip extension of 32.04º, when corrected for the unreliable starting position, produces a range of 22.04º. Likewise, this study's MTT range of -9.10º, when corrected for the imprecise starting position, yields an angle of -19.10º. This correction sees a 2.94º difference between the hip extension and MTT ranges. Thus if the starting position error is recognised, the two hip extension testing positions enjoy a greater degree of concurrence than has previously been reported.

In conclusion, this study's measurement inaccuracies are both unique and universal. The angulation and siting of the IMU was specific to this research, however, ignoring the starting position angle is a feature, unacknowledged and likely ignored in earlier investigations (Peterson Kendall et al., 1993; Clarkson, 2013; Beneck et al., 2018 Roaas and Andersson, 1982; Clarkson, 2000; Klassbo et al., 2003). This study's IMU is reliable, accurate and permits the lone clinician ease of use. Being able to accurately measure hip range, aids diagnostics and treatment. The next step, the possible development of a mechanical tool to establish sagittal plane hip joint neutral, would further these endevours. A theoretical means of finding sagittal plane hip joint neutral, making exclusive use of the lateral epicondyle, is discussed in Appendix J below.

Appendix J

Rationale for the Theoretical Means of Finding Sagittal Plane Hip Joint Neutral, Making Exclusive Use of the Lateral Epicondyle

We imagine a circle, with the femoral head's axis of rotation located at its origin, the femoral shaft its radius and the lateral epicondyle thereby a point that moves along its circumference. A ruler is placed on the plinth, along its length, under the participant's distal thigh. A plumb-line is attached to the lateral epicondyle. This perpendicular, dropping down from the lateral epicondyle onto the horizontal plane (ruler) below the "circle", intersects the horizontal plane at different points as the femoral shaft moves through the sagittal range. As the hip is moved from a flexed position toward neutral, so the plumb-line moves distally along the ruler. Similarly, as the hip passes through neutral into extension, the plumb line edges proximally, toward the hip once again. Therefore, hip joint neutral is attained and corresponds to the most distal point traversed by the plumb-line along the ruler. In this position, the lateral epicondyle and the femoral head's point axis of rotation are level and the femur is parallel to the horizontal plane below (see Fig. J1 below). This position would have served as the sensor's calibration (starting) point for hip flexion, extension, SLR and neutral for the MTT.

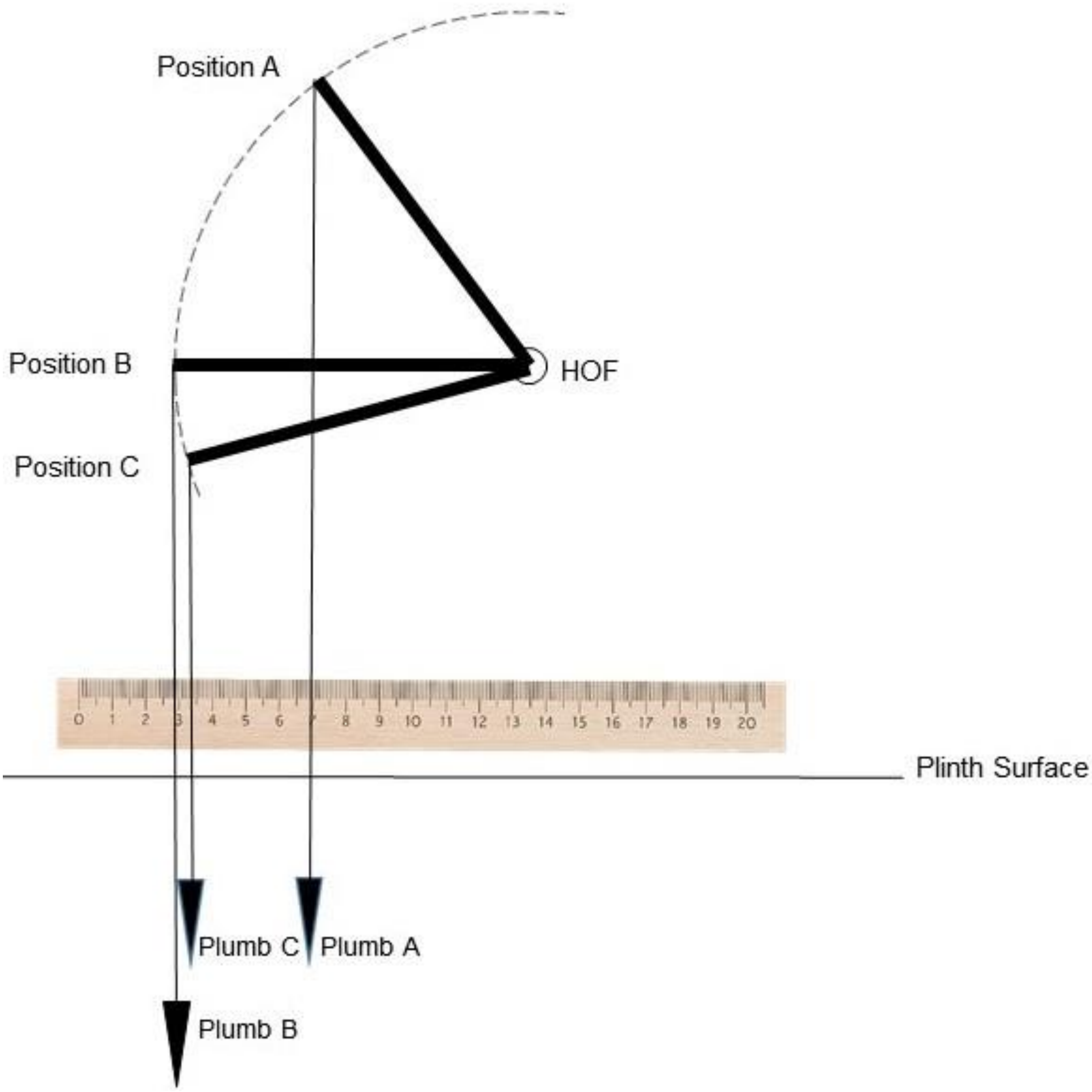

Fig. J 1 Schematic diagram illustrating different sagittal positions of the femur (bold, thick lines). The origin of the circle, corresponding with the point axis of rotation of the head of the femur is demarcated by point HOF. Position A representing 55º of hip flexion with its plumb-line (plumb A) intersecting the ruler on the plinth's surface. Position C representing a smaller angle, -15º hip flexion (or 15º hip extension), with its plumb-line (plumb C) intersecting the ruler at a more distal location. Position B, where the lateral epicondyle and the point axis of rotation of the head of the femur are perfectly level, indicated by the most distal point (plumb B) reached by the plumb-line along the ruler's surface, marks 0º in the sagittal plane.

Tested during the pilot study, the plumb-line's pendular movement hindered detection of the hip neutral position. The researcher constructed a plumb-line with a mechanism which he hoped would dampen the swing, but once again recognising the calibration point proved difficult. Replicating that participant's proportions, a 1:1 scale diagram drafted with a 34cm radius on a piece of paper, 10 cm above a baseline, revealed the problem. This was later corroborated using ECG graph paper, a 0.5 mm clutch pencil, a transparent protractor (Maped Canada Inc, Montreal Canada) and a metal ruler (Foska, China). A 5^{o} arc of movement of the femur/radius correlated to approximately 1.25 mm movement of the plumb-line on the ruler below. Therefore, identifying a 1^{o} movement of the femur correlated to approximately 0.25 mm of the plumb-line along the ruler. This proved that finding the hip neutral position with this tool was theoretically possible but not practically feasible. Using it, would necessitate the complete elimination of plumb-line swing, a plumb-line thread less than 0.25 mm in width and suitable magnification to be able to discern plumb-line movements to a fraction of a millimetre. In total, a task beyond the abilities of this researcher.

Appendix K

Turnitin Report

Dissertation Final Draft 20230401

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