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Understanding Knee Joint Laxity in the Clinical Assessment of Anterior Cruciate Ligament Injuries

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Statement of Originality

I declare that all of the work within this thesis is my own and any sources used are appropriately referenced.

Natasha Allott

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Abstract

Anterior cruciate ligament (ACL) injuries are prevalent, debilitating, and impose significant costs on both patients and healthcare systems. Characterised by increased joint laxity and compromised stability, these injuries present substantial challenges in clinical diagnostics due to the inherent subjectivity and difficulty in quantifying joint laxity.

This thesis investigates current clinical pathways and diagnostic challenges associated with ACL injuries to identify areas for improvement. It evaluates kinematic variations between ACL-injured individuals and uninjured controls using optical motion capture during laxity tests and gait analysis. It also investigates muscle activity by analysing electromyography (EMG) activity during these assessments. Additionally, the potential of wearable sensors to detect kinematic markers of laxity during clinical evaluations is explored.

Through systematic and scoping reviews, as well as surveys, this research highlights the subjectivity in laxity assessment as a major barrier to accurate and timely diagnosis. A cohort study comprising measures of motion capture, EMG and IMU sensor data explores the kinematic differences between the ACL injured and healthy cohorts, with a view to facilitating the clinical diagnostic and management process. Motion capture data reveal statistically significant increases in anterior and anteromedial rotary laxity in ACL-injured individuals, with variations influenced by the specific clinical tests administered. Gait analysis further underscores distinct differences in kinematic behaviours, demonstrating altered walking patterns that reflect compensatory strategies to mitigate instability. EMG results suggest that different clinical tests affect muscle guarding responses, reinforcing the need for a battery of comprehensive joint laxity and functional movement assessments.

Finally, a machine learning model developed from IMU sensor data captured during laxity testing illustrates the diagnostic potential of wearable technologies. This model enhances diagnostic accuracy and offers a promising avenue to revolutionise patient care by integrating objective measures into routine clinical assessment.

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Abbreviations

ACL – Anterior Cruciate Ligament

MCL – Medial Collateral Ligament

PCL – Posterior Cruciate Ligament

LCL – Lateral Collateral Ligament

ALL – Anterior Lateral Ligament

ROM – Range of Movement

ATT – Anterior Tibial Translation

AMRL – Anteromedial Rotary Laxity

AP – Anterior-Posterior

ER – External Rotation

IR – Internal Rotation

IMU – Inertial Measurement Unit

OMC – Optical Motion Capture

EMG – Electromyography

EMS – Electromagnetic Systems

ML – Machine Learning

AI – Artificial Intelligence

MRI – Magnetic Resonance Imaging

PTOA – post-traumatic osteoarthritis

OA – Osteoarthritis

A&E – Accident and Emergency

MSK – Musculoskeletal

HLI – Healthy Leg of the ACL Injured Participants

ASIS – Anterior Superior Iliac Spine

PSIS – Posterior Superior Iliac Spine

Fem – Femoral

Tib – Tibial

Epi – Epicondyle

Con – Condyle

Med – Medial

Lat – Lateral

TibTub – Tibial Tuberosity

Results Calculation Abbreviations

*MaxMaxNorm = The ratio of ATT using the **maximal** displacement induced over multiple reps on one leg and the maximal displacement induced over multiple reps of the contralateral leg.*

*MeanMeanNorm= The ratio of ATT using the **mean** displacement induced over multiple reps on one leg and the mean displacement induced over multiple reps of the contralateral leg.*

1. Introduction

1.1. Background and Motivations

Anterior cruciate ligament (ACL) injuries represent a significant clinical challenge and are among the most common and debilitating knee injuries, particularly affecting athletes and physically active individuals (1). Annually, these injuries impact millions globally, leading to a substantial socioeconomic burden due to assessment and surgical costs, rehabilitation, and loss of patient function and productivity (2). In healthcare systems like the NHS, ACL injuries contribute to long-term financial strains and resource allocation challenges due to high treatment costs and extended recovery periods (3).

The long-term repercussions of ACL injuries extend beyond immediate pain and disability. Individuals with a history of ACL injuries have a significantly increased risk of developing post-traumatic osteoarthritis (PTOA) (4, 5). PTOA can lead to chronic pain, reduced quality of life, and further economic impact due to ongoing healthcare needs and reduced capacity to work (6). The progression to PTOA following an ACL injury highlights the need for accurate and timely diagnoses and effective management strategies to mitigate secondary health complications (5).

The management of ACL injuries begins with accurate and timely diagnosis, as this is critical for optimal recovery outcomes. However, current diagnostic processes in acute emergency settings are fraught with challenges (2, 7). Delayed or inaccurate diagnosis is common, stemming from the limitations in clinical assessments and standard imaging techniques (7, 8). These limitations not only increase the risk of improper treatment but also exacerbate the socioeconomic impact by prolonging recovery and potentially leading to secondary complications such as PTOA by not restoring joint functionality early (9).

The assessment and management of ACL injuries are guided by established recommendations from authoritative bodies such as the National Institute for Health and Care Excellence (NICE) and the British Orthopaedic Association (BOA). According to NICE guidelines, a comprehensive clinical assessment should include a detailed patient history and physical examination to evaluate knee pain, identify joint instability, and assess ligamentous integrity through clinical tests like the anterior drawer and Lachman tests (10). Key signs that clinicians are advised to look for include lateral knee and joint line tenderness, a positive Lachman test,

and positive anterior drawer or pivot shift tests. However, NICE has identified that the diagnostic accuracy of these tests can be poor, particularly when performed by non-specialists. This variability in accuracy is an important consideration for clinicians, as it highlights the potential for an inaccurate or missed diagnoses, underscoring the need for clinicians to be cautious in solely relying on these assessments for diagnosis (10). To mitigate these limitations, NICE recommends that when clinical findings are inconclusive or further confirmation is necessary, imaging techniques such as MRI should be employed to support and validate the diagnosis of ACL injuries. This comprehensive approach aims to enhance diagnostic confidence and facilitate appropriate management.

The BOA echoes these points, emphasising the importance of structured pathways for early and accurate diagnosis to minimise the risk of long-term complications, such as post-traumatic osteoarthritis (PTOA). The BOA's best practice guidelines advocate for multidisciplinary approaches that integrate physical assessments, imaging, and evidence-based rehabilitation protocols. This approach ensures that both the acute and long-term impacts of ACL injuries are addressed effectively, supporting patient recovery and joint health (11).

Despite advancements in clinical practices, the assessment of knee laxity—an essential factor in diagnosing ACL injuries—remains imprecise (8). Traditional clinical assessment methods rely on subjective clinical judgment (and clinical experience) and may not capture the biomechanical changes indicative of early or partial ACL injuries (7) (12). This reliance on subjective assessment represents a significant knowledge gap and presents problems and delays in patient pathways. The integration of these best practice guidelines into clinical protocols highlights the need for objective diagnostic tools. Incorporating technologies that offer more reliable, objective measurements aligns with the goals of these guidelines, reducing diagnostic variability and ultimately improving patient outcomes. However, the available tools that have the capacity to objectively measure knee laxity have questionable accuracy and subsequent low use in the clinical world (13). Enhancing our understanding of knee biomechanics by using novel modelling techniques and optical motion capture during ligamentous tests could facilitate a more nuanced interpretation of these assessments and establish a baseline understanding of knee mechanics that can be deployed in developing diagnostic tools suitable for use in clinical settings.

There are several gaps in the current research related to the management of ACL injuries. The BOA guidelines highlight the patient-centred approach required when choosing between surgical and conservative management for ACL injuries (11). Surgical reconstruction is recommended for individuals needing high knee stability, such as athletes, to restore joint function and prevent further damage, while conservative management can be effective for those with lower activity demands, focusing on strengthening surrounding muscles to maintain stability. The role of bracing is acknowledged as potentially beneficial during rehabilitation or specific activities, but its long-term efficacy is uncertain, and its use should be tailored to individual needs. Comprehensive rehabilitation is emphasised as essential, whether surgery is performed or not, with pre-operative (prehabilitation) and post-operative physiotherapy playing crucial roles in enhancing recovery and reducing reinjury risk. This variability in treatment options underscores the importance of collaborative decision-making between patients and healthcare providers to align care with the patient's lifestyle, goals, and knee stability requirements.

There is a need for objective tools that can provide reliable measurements of knee laxity. The tools currently available for objectively measuring knee laxity often lack accuracy and are infrequently used in clinical practice. This limits their utility in improving diagnostic outcomes. There is a need for a deeper understanding of knee biomechanics, particularly in how biomechanical changes however subtle, can indicate partial ACL injuries, or provide indications of injury that facilitate earlier more timely diagnosis. Such understanding could inform the development of more precise diagnostic tools, potentially provided through new sensing technologies. While wearable sensor technologies and machine learning models show promise, their integration into clinical settings for the diagnosis of ACL injuries is still in its infancy. More research is needed to validate their effectiveness and practicality in real-world applications. There is limited research on how improved diagnostic tools and techniques can impact long-term patient outcomes, particularly in preventing secondary complications like PTOA. This thesis aims to bridge these gaps by enhancing the objectivity and accuracy of ACL injury diagnostics through innovative approaches.

Wearable sensors offer the potential to quantify biomechanical parameters in real-time, providing continuous, dynamic, and objective data that are unattainable using conventional clinical examinations (14, 15). When coupled with advanced machine learning techniques,

specifically neural networks, these data can be transformed into accurate, reliable diagnostic insights, supporting clinicians in making informed decisions quickly (16).

By advancing the integration of wearable technologies and machine learning into ACL injury diagnostics, this thesis not only addresses the immediate need for improved clinical assessments but also contributes to innovative solutions for reducing the overall burden on healthcare systems and enhancing patient outcomes. Through this research, it aims to set the foundations for a new paradigm in the management of knee injuries, where technology-enabled solutions drive clinical decisions and patient triage, optimising both cost-effectiveness and care quality.

1.2. Project Aims and Objectives

Given the challenges associated with delayed and inaccurate ACL diagnoses and their costly repercussions for both patients and the healthcare system, coupled with the subjective nature of assessing knee laxity, this thesis aims to enhance the understanding and quantification of knee laxity within the ACL-injured population. This goal is achieved through using optical motion capture - the gold standard in biomechanics analysis during clinical laxity testing and gait assessment. Once a biomechanical ground truth of kinematics is obtained, the thesis explores the compensatory muscle activity during laxity assessment and the potential of using wearable sensors as a diagnostic tool in ACL injuries.

The objectives to fulfil this aim were as follows:

- Conduct a comprehensive literature review of the current clinical timeframes and diagnostic accuracy associated with ACL diagnosis and to identify key areas for improvement.
- Identify and analyse discrepancies in clinical viewpoints within the standard care pathway, highlighting variations in diagnostic approaches and their implications.
- Scope the current landscape of devices available for quantifying knee laxity, evaluating their effectiveness and potential limitations.
- Develop a sophisticated biomechanical model of the knee that accurately quantifies detailed changes in knee laxity across different planes of motion.

- Characterise knee laxity across a protocol containing multiple clinical tests and surrogate functional markers of knee laxity in the ACL injured population.
- Design and develop a machine learning model to explore the potential of integrating wearable technology as a reliable diagnostic tool in clinical settings.

1.3. Summary of Contributions

This research significantly enhances the clinical understanding of knee laxity in ACL-deficient patients and pioneers advancements in the application of wearable technology within clinical settings. The tangible contributions of this thesis are summarised as follows:

- **Systematic Review:** An extensive review of the clinical literature was performed to evaluate the current diagnostic pathways for ACL injuries, their diagnostic accuracies, and the typical timeframes involved. This review has established a comprehensive overview of current clinical practice from which improvements in diagnostic processes can be proposed.
- **Clinician Survey:** A detailed survey of clinicians was conducted to ascertain their priorities in assessing and managing knee injuries. The findings from this survey have identified critical areas requiring service improvements and have informed the development of enhanced clinical protocols.
- **Scoping Review on Devices:** A scoping review of the existing devices capable of quantifying knee laxity in patients with acute ligament injuries was undertaken. This review assessed the state-of-the-art in measurement technologies, highlighting gaps and opportunities for technological enhancements.
- **Biomechanical Protocol Development:** A novel protocol using motion capture systems, electromyography (EMG), and inertial measurement unit (IMU) sensors was developed. This protocol allows for data-rich collection of information on knee laxity during clinical assessments, providing a robust method to capture dynamic knee behaviours that were previously unquantifiable.
- **Machine Learning Model Development:** A machine learning model was developed as a proof of concept to diagnose ACL tears using wearable sensors. This use of wearable sensors for this clinical context is novel in the field of MSK diagnostics. This model demonstrates the feasibility of integrating advanced

analytical techniques with wearable technology to improve the accuracy and efficiency of ACL injury diagnostics and triage.

1.4. Publications and Conferences

The following systematic review was published by the author of this thesis while undergoing this doctoral work.

- Allott NEH, Banger MS, McGregor AH. Evaluating the diagnostic pathway for acute ACL injuries in trauma centres: a systematic review. *BMC Musculoskeletal Disorders* 2022;23(1):649.

Work was presented in the following conferences which was included in aspects of this thesis:

- **British Orthopaedic Sports Trauma and Arthroscopy Association (BOSTAA):** podium talk - Quantifying Anteromedial Rotational Stability in Anterior Cruciate Ligament Injured Patients with Associated Collateral Involvement.
- **British Association of Sports and Exercise Medicine (BASEM):** Poster – Quantifying Knee Joint Laxity: Considerations for Assessing the Injured ACL.
- **British Association of Sports and Exercise Medicine (BASEM):** Poster alongside BSc Student– Investigating muscle guarding during knee laxity testing in those with ACL tears and their healthy controls

1.4.1. Proposed Publications

The following publications hope to be submitted for review based on this thesis.

- A review of the current methods to quantify knee laxity. – *A Scoping review* (submitted for publication and awaiting decision)
- Modelling Anterior Tibial Translation with Optical Motion Capture Systems: A Clinical Assessment Approach- *Methodological paper*
- Modelling Anteromedial Rotary Laxity with Optical Motion Capture Systems: The Feagin Thomas test- *Methodological paper*
- Early Detection of ACL Injuries Through IMU-Based Machine Learning: A Feasibility Study: Initial findings – *Original Research Article*
- Obstacles and Discrepancies in ACL Assessment and Management: A Survey of Healthcare Specialists- *A survey report*

1.5. Thesis Structure

This thesis is organised into several chapters, starting with this introductory chapter, which provides a navigation for this research. Each chapter is designed to progressively build upon the previous one, forming a cohesive narrative that addresses the complexities of ACL injury diagnostics through innovative biomechanical and technological approaches.

Chapter 2: Current Clinical Practice

Chapter 2 examines the broader impact of ACL injuries on both individuals and healthcare systems. It delves into the clinical challenges associated with these injuries, emphasising the high costs and long recovery periods. A systematic review is presented, which critically assesses the current diagnostic pathways utilised in emergency care settings for ACL injuries, highlighting areas in need of improvement.

Chapter 3: Obstacles and Discrepancies in ACL Assessment and Management

Chapter 3 includes a detailed survey which clinicians completed. It explores existing discrepancies and variations in the diagnosis and management of ACL injuries, revealing key insights into clinical practices and identifying potential areas for improvements in ACL assessment and management.

Chapter 4: The Biomechanics of Knee Laxity

Chapter 4 introduces knee laxity and stability from a biomechanical perspective. It discusses the various manifestations of laxity associated with ACL damage and reviews current devices capable of quantifying this laxity, summarising the state of the art in measurement technology.

Chapter 5: Development of the Methodology for Assessing Laxity with OMC Systems

This chapter underpins the methodology used to capture and calculate measures of knee laxity and knee kinematics. It provides details regarding participant recruitment, the marker system set up, sensor placement, and testing protocol. It also explains the analysis techniques

of the motion capture laxity calculations, and details the measures taken to reduce data errors. The methodological protocol and participant information remain consistent with the data shown in chapters 6-9.

Chapter 6: Quantifying Knee Laxity using Motion Capture

This chapter details the results of the VICON motion capture analysis regarding knee laxity. It explores the differences in laxity outputs across multiple clinical tests and hopes to inform clinical assessment. It also looks at how other factors influence knee laxity in the injured population and compares the values of laxity obtained through OMC systems with standard arthrometry.

Chapter 7: The Effects of Muscle Guarding During Laxity Assessment

Chapter 7 assesses the muscle guarding effects captured by EMG data observed in both cohorts during clinical testing. It provides an in-depth analysis of muscle activity, offering insights into compensatory mechanisms at play during knee laxity tests.

Chapter 8: Gait Analysis Using Motion Capture

This chapter presents a gait analysis performed using the VICON system to highlight biomechanical differences during functional movement between ACL-injured participants and healthy controls. The analysis also investigates how injury timing influences gait patterns.

Chapter 9: The Use of Wearables in ACL Diagnosis

Chapter 9 explores the application of inertial measurement unit (IMU) wearable sensors as diagnostic tools for ACL injuries. It details the development and validation of a machine learning model, specifically a neural network, which analyses data from the wearable sensors to distinguish between injured and healthy participants based on joint laxity markers.

Chapter 10: Conclusions and Future Work

Chapter 10 is the summation chapter which encapsulates the overall findings of this research and explores the future work which would be advantageous to further innovation and clinical improvements in this field.

2. Current clinical practice

This chapter explores the complexities of knee anatomy and reviews the incidence and mechanism of ACL injuries. Furthermore, it investigates the assessment process and the clinical diagnostic pathway for acute knee injuries, before examining the associated timeframes and diagnostic accuracy of these associated assessment methods. Within this chapter lies a systematic review that has been published in the BMC musculoskeletal journal (7).

2.1. Knee and ACL Anatomy

The knee is a complex and multifaceted weight-bearing joint, comprising of an interplay of bones, ligaments, tendons, and cartilage, which collectively facilitate movement and ensure stability. Ligamentous integrity is critical in restricting abnormal movements and ensuring correct joint alignment in order to control joint range. Whilst not to devalue the importance of some of the more intricate structures, the knee is comprised of 4 major ligaments that contribute to maintaining joint stability; the Anterior Cruciate Ligament (ACL) and the Posterior Cruciate Ligament (PCL) are the two intracapsular cruciate ligaments preventing anterior and posterior tibial translation respectively; with the joint supported further by the Medial Collateral Ligament (MCL) and Lateral Collateral ligament (LCL) which ensure valgus and varus stability; they are extra-articular sitting more superficially to the skin. Unlike the hip; the knee is inherently unstable as it has a much smaller congruency of articulating surfaces, thus the ligaments have a much greater role in maintaining joint stability (17).

Whilst the meniscus also contributes to knee stability, its role differs from that of ligaments; rather than connective fibrous tissue, the meniscus is cartilaginous and acts as a shock absorber between the femur and tibia; it acts to enhance the anatomical stability by increasing joint congruency. It is C-shaped and spans the perimeter of the lateral and medial knee surface, optimising weight distribution as well as playing a role in joint lubrication. Whilst the focus of this research is on the ACL predominantly, concomitant injuries are common to the meniscus and other ligamentous structures. For this reason, these structures will be mentioned in conjunction with the ACL throughout this thesis.

The ACL originates in the medial wall of the lateral femoral condyle 25-30% of the postero-anterior dimension of the Blumensaat line, it inserts into the intercondylar area of the tibia at

44 to 50% of the antero-posterior tibia dimension and at 44 to 50% of the medio-lateral tibia dimension (18). The ACL is divided into the anteromedial and posterolateral bands of fibres, the former contributes to preventing anterior translation (resisting 90% of the anterior displacement force) (17), leaving the posterolateral bands' primary role to provide stability in knee extension (19).

As well as preventing anterior tibial translation, the ACL contributes to preventing external rotation (18). The ACL tightens during terminal extension during the screw-home mechanism, when the collateral ligaments tighten in extension, external rotation of the knee is a consequence of a prolonged anterior glide of the medial side of the knee and the need for joint congruency in the lateral condyle (20). This helps stabilise the knee during extension (19, 20) and prevents subluxation and anterior translation during deep flexion (17, 19).

ACL injuries are often accompanied with MCL damage, around 42% of ACL injuries have associated MCL fibre disruption, making it one of the commonest concomitant injuries (21, 22). The MCL is divided into superficial and deep fibres, the former plays a primary role in ensuring valgus stability of the knee, the later contributes to maintaining rotational stability and more specifically anteromedial rotary stability. The Superficial MCL has one femoral attachment that sits 3.2mm proximal and 4.8mm posterior to the medial epicondyle and has 2 insertional points, one into soft tissue 12.2mm distal to the joint line and the second sits in with the pes anserine bursa (23, 24). The LCL sits on the lateral side on the knee and is the primary restraint to varus forces and can provide some assistance against external rotation in lower degrees of knee flexion (23), it attaches 1.4mm proximally and 3.1mm posteriorly to the lateral epicondyle and attaches distally to the fibular head (23). The PCL originates from the lateral aspect of the medial femoral condyle and inserts posterior and lateral to the articular plateau of the tibia (24). The PCL also has 2 bundles and is larger than the ACL, its role is to prevent posterior tibial translation, but the incidence of injury is much lower than that of the ACL (23).

Although other smaller structures also contribute to the overall structural integrity of the knee, a detailed exploration of these is beyond the scope of this PhD project.

2.2. Incidence and Prevalence of ACL injuries

Anterior cruciate ligament (ACL) injuries are a significant concern in the field of sports medicine, primarily affecting athletes involved in high-demand sports like football, basketball, and skiing (25). The prevalence and incidence of ACL injuries reveal significant trends and differences based on age and sex. The age group most at risk includes individuals aged 15 to 45, due to their higher engagement in athletic activities (26). The incidence rate of ACL injuries is estimated at approximately 68.6 per 100,000 person-years, with a notable prevalence in female athletes (26), who are 2 to 8 times more likely to sustain this injury compared to their male counterparts (27). This increased susceptibility is often attributed to a combination of anatomical, biomechanical, hormonal, and neuromuscular differences between sexes (27). For example, one biomechanical difference is that women land with greater peak knee abduction angles than men which is known to put increased strain on the ACL potentially contributing to the increased incidence of ACL injury among women (28). Also, factors including the smaller size of the intercondylar notch in women, which is the groove in the femur through which the ACL passes, and a tendency towards an imbalanced quadriceps/hamstring ratio may also contribute to this higher risk of injury (29).

2.3. ACL Mechanism of Injury

Most ACL injuries have a clear injury mechanism where excessive strain is exerted on the fibres of the ligament; this can be from contact or non-contact force. In 90% of knee injuries in sport (30), the rupture of an ACL typically occurs when the knee is loaded during fast changes of direction, a twisting plant and pivot mechanism, or after landing in excessive hyperextension (31). The high frequency and commonalities among ACL injuries stress the importance of robust, reliable, and reproducible diagnostic measures.

2.4. Clinical Assessment

ACL tears are debilitating, causing a substantial reduction in normal function; most patients present acutely to a trauma assessment centre. The ACL is currently assessed through joint stability tests, subjective assessment markers, and radiological imaging. Often, it is the combination of the above that alludes to a diagnosis rather than any in isolation (32). Each of these assessment methods are accompanied by their individual barriers to assessment.

The absence of the ACL gives rise to an increase in anterior tibial translation. The amount of anterior translation is assessed using joint stability tests which involve passively moving the

joint into vulnerable positions to assess for laxity in different planes of motion. Within the context of the ACL, the focus of these instability tests is assessing for anterior and rotary excessive movement (20, 33). As expected, the amount of laxity is dependent upon several variables; swelling, pain, severity of rupture, and assessor experience are the three main factors that influence the assessment (34, 35). This laxity is typically assessed through different variations of clinical tests, such as: the anterior drawer test, the Lachman test, and the pivot shift test, all of which require the joint to be in different positions while the assessor applies force. The goal is to elicit the maximal amount of joint laxity whilst ensuring the patient is relaxed; due to joint effusion, pain and associated involuntary muscle guarding the accuracy of these clinical tests can be varied.

Currently, the core device available measure to quantify instability is a KT1000 – a type of arthrometer, which measures anterior instability whilst tibiofemoral anterior translation is induced by the clinician, a side-to-side difference between the injured and healthy leg of 3mm or more is considered indicative of injury (36). Historically, this tool is the one that has been widely used within the clinical setting to quantify joint laxity, although it has not been proven to be reliable or repeatable, nor is it user-friendly due to its size (37).

Subjective markers indicative of ACL injury consists of the following: pain, swelling, reporting of a 'pop' at the time of injury, episodes of giving way, and difficulty weight bearing. However, these symptoms are not specific to an ACL rupture, they difficult to quantify, and are reliant on the patient's report (25, 35, 38).

2.5. Timeframes to Diagnosis and Clinical Care Pathway

Due to the trauma mechanism associated with ACL injury, patients generally access care through emergency care services. Whilst pathways vary depending on the access and care provisions of the healthcare trust, generally patients are initially assessed by a non-specialised clinician who triages the patient and provides acute management advice (39). If they are suspicious of ligamentous injury, patients are referred to a specialist clinic where they are assessed in more detail.

Initial assessments before MRI rely heavily on the outcome of laxity assessments, which are subjective and can lead to prolonged and inaccurate ACL diagnoses. (35). MRIs and arthroscopic diagnostic surgeries, whilst accurate are extremely costly and with limited access

which makes them unattainable for all acute knee injuries. Thus, many patients endure long periods of uncertainty regarding their injury and subsequent delayed management. Long periods of uncertainty can manifest in delayed or misdirected rehabilitation, increased risk of secondary knee damage, multiple or repeated examinations or repeat of injury mechanism (9) (39).

As part of this thesis, an evaluation of the assessment process including diagnostic timeframes and accuracy within the A&E pathway was undertaken through a systematic review, details of which are later discussed in this chapter (section 2.10).

2.6. Injury Verification: Gold Standard of Diagnosis

Clinicians rely on radiological evidence to confirm diagnosis; magnetic resonance imaging (MRI) is currently considered to be one of the gold-standard diagnostic techniques for ACL injury. MRIs are accurate and reliable at demonstrating the extent and location of trauma, not just to the ACL but to the surrounding structures which may be concomitantly injured in the event of ACL rupture. Despite their effectiveness, they are expensive, costing the NHS two billion pounds per annum (40), and are associated with long wait times which has been compounded further as a result of the 'back log' and stress on clinical services created by the coronavirus pandemic (41, 42); between June 2020 and August 2021, the waitlist for an MRI increased by 50% (43), making them unattainable for immediate use for every patient with a knee injury (35). Furthermore, the quality of report is subjective and highly dependent on the interpreting radiologist, specialist training is required to be able to do this, thus leading to further delays.

X-rays and ultrasound can also aid in the ACL assessment process, each having a slightly different purpose. X-rays, although more readily available than MRIs, only provide detail of the bony pathology and cannot show soft tissue structures, as such they are used simply to rule out a fracture. Ultrasound provides low-cost, portable means of imaging tissue structures, however the real time image production conduces it to be an operator dependent modality (44). Whilst ultrasonography is a well-established method to observe more superficial structures to the knee, it was thought that the ACL was poorly visualised by ultrasound however recent papers have reported high diagnostic sensitivity: 88%, and specificity: 96% (45).

The other gold standard diagnostic verification is for patients to undergo a surgical arthroscopic procedure (46). These are costly, invasive, and have long wait times(47). Arthroscopy can be used for diagnostic or treatment purposes. Despite extensive clinical assessment and imaging verification, surgeons rely on arthroscopy to evaluate the extent of the damage (48). . It would therefore be impractical and inappropriate for every suspected ACL injury to routinely go for arthroscopy, due to the increased risk and associated harm associated with unnecessary surgery (49)

2.7. Calculating Diagnostic Performance Characteristics

With new and current assessment tools it is important to understand a range of parameters that affect their utility including the efficacy, reliability, repeatability, and accuracy.

The ability of a diagnostic test to identify the presence or absence of disease is of importance to this project, it is therefore of importance to understand how accuracy and its related metrics are calculated (27). When basing diagnoses on an assessment method, diagnostic performance characteristics must be considered when interpreting test results (27, 28).

Clinicians need to evaluate the confidence in the test they perform when they use their results to indicate pathology. When reviewing individuals for ACL injury, they can either be classed as patients (ACL-Injured) or healthy (not injured); where patients are positive for injury and healthy are negative (28). Within this, there can be positive and negative results that can either be true or false.

True positive (TP) = number of cases correctly identified as patients

False positive (FP) = number of cases incorrectly identified as patients

True negative (TN) = number of cases correctly identified as healthy

False negative (FN) = number of cases incorrectly identified as healthy

From the true or false, negative, or positive results; sensitivity, specificity, negative predictive values (NPVs), and positive predictive values (PPVs) can then be calculated using equations. These calculations derive from the articles by Shreffler et al (27) and Baratloo et al (28).

NPVs calculate the negative results (healthy patients) produced by the diagnostic test, and more specifically how many of these are true negatives.

$$NPV = TN / (TN + FN)$$

PPVs calculate the positive results (injured patients) produced by the diagnostic test how many are reflective of true positive cases.

$$PPV = TP / (TP + FP)$$

The sensitivity of an assessment method is the ability to detect the number of patients in the population.

$$Sensitivity = TP / (TP + FN)$$

Whereas the specificity of a test is the ability to detect the number of healthy individuals in the population

$$Specificity = TN / (TN + FP)$$

Ultimately each subcomponent contributes to the overall value of assessment accuracy, which provides the ability to distinguish the injured and healthy patients appropriately.

$$Accuracy = (TP + TN) / (TP + TN + FP + FN)$$

The problem with the current assessment methods for ACL injury is that there is not an established method that can produce high accuracy, is readily available, low cost, and does not depend on operator experience. In theory, any clinician can perform laxity tests, however, due to the unquantifiable nature and high subjectivity of these tests, the diagnostic performance characteristics vary greatly. Conversely, radiological and surgical verification is generally associated with much higher degrees of accuracy, this is unsurprising due to the visual morphological confirmation it provides; however, radiology is expensive and not usually accessible in the timeframes required. Diagnostic accuracy and complexities around ACL diagnosis are explored within the systematic review conducted (section 2.10).

2.8. Post-Traumatic Osteoarthritis (PTOA)

The link between Anterior Cruciate Ligament (ACL) injuries and the development of post-traumatic osteoarthritis (PTOA) is a subject of ongoing debate. Eighty seven percent of ACL tears lead to PTOA(1). PTOA is hypothesised to be caused by the degradation of cartilaginous structures and metabolic breakdown; abnormal biomechanics and the inherent instability created by the ACL injury, which is believed to either cause or expedite arthritic changes (4).

Furthermore, the presence and progression of PTOA following injury is influenced by a combination of structural, neuromuscular, mechanical and biological factors (5).

Structurally, damage to the ACL can result in compromised stability and increased strain on the structures of the joint. High-energy injuries often lead to damage to the cartilage, meniscus, and subchondral bone (5). Cartilaginous trauma can stimulate matrix-degrading enzymes and inflammatory cytokine production which can initiate chondrocyte necrosis and apoptosis (4). The poor vascular supply and limited healing capabilities of cartilage can also contribute to PTOA progression(1).

The meniscus is essential in the knee's ability to enable even weight distribution across the joint, the meniscus is one of the most concomitantly injured structures when ACL injuries occur (50). The meniscus is biologically active, secreting enzymes and inflammatory mediators, when the integrity of this structure is compromised, there is a subsequent loss of weight distribution, changing loading throughout the joint, thus accelerating knee degradation (51).

Up to 90% of ACL injuries have affiliated subchondral bone (SB) loss (1). Bone marrow disturbance can cause osteocyte necrosis which is accompanied by proteoglycan loss and chondrocyte injury (5). The bone then undergoes the remodelling phase in which there is a careful balance between resorption and bone formation (52, 53), ACL injuries disturb this process which can lead to morphological change to the SB altering the mechanical load dispersion in the cartilage (53).

Neuromuscular adaptations are another potential contributor to the PTOA mechanism theory (5). Quadriceps and hamstrings deficits are common post ACL injury, the resultant change in muscle patterning affects the load distribution across the joint (54, 55). Atrophy and abnormal muscular co-contraction can also reduce joint stabilisation and reduce the shock-absorbing and load distribution contribution of these contractile structures (5). The ACL also provides a degree of neuromuscular and proprioceptive feedback to the knee (54). Thus, loss of ACL integrity can alter the information given to the central nervous system which can directly impact the motor output thus changing joint mechanics (5).

The ACL is a major contributor to joint stabilisation, it works symbiotically with the other ligamentous structures in maintaining correct loading patterns and joint kinematics in the

knee. When knee mechanics are altered, the loading on these surrounding structures changes, potentially expediting degradation processes (5). Abnormal loading can cause changes to chondrocyte metabolism, proteoglycan production, collagen fibre orientation, and MMP expression which in turn act to modify the mechanical properties of the cartilaginous structures (5, 51). This explains how mechanically, altered loading patterns and joint kinematics post-injury can accelerate joint degeneration.

Biologically, inflammatory responses and alterations in cellular activity contribute to cartilage degradation (56). An increase in oxygen free radicals, inflammatory cytokines, molecular biomarkers, and degradative enzymes are all factors that can contribute to chondrocyte degradation, disturbance to the extracellular matrix, osteophyte production, and overall change in the joint's natural homeostasis (1, 5, 51). These interrelated structural, mechanical, molecular, and neuromuscular factors collectively work synergistically to drive the degenerative changes characteristic of PTOA (5).

Current clinical criteria, like the Kellgren–Lawrence and Outerbridge classification schemes, are often used in diagnosing OA on plain radiographs but are not be able to detect early changes (57). MRI has emerged as a valuable tool for evaluating joint tissues following traumatic injuries and can provide sophisticated analysis of the severity and progression of such (51). There is also a focus on the early detection of PTOA through biomarkers in blood, serum, and synovial fluid (6, 58). Whilst research is ongoing in the early detection of PTOA following ACL injury, such morphological changes once noted are irreversible, and the progressive nature of this degeneration is inevitable. With such a large proportion of the ACL-injured population at risk of arthritic changes, there is a need for preventative measures and earlier diagnostic abilities in order to provide the most efficient intervention strategies when injuries occur.

2.9. Repercussions of Delayed Diagnosis

Early diagnosis is paramount to ensure appropriate intervention that not only manages the injury but reduces the chance of secondary injuries to surrounding structures (22). Isolated ACL tears with no concomitant injury damage are rare. A meta-analysis in 2022 looking at concomitant injury patterns alongside ACL rupture found that bone bruising occurred in 91.9% % of patients, associated LCL injuries occurred in 32.3%, MCL was affected in up to 49.4% of cases, and the anterolateral Ligament (ALL) (notoriously hard to visualise on MRI)

was affected 17-88.2% of the time (59). Sadly, there is evidence that even if associated structures are not injured at the time of injury, ACL deficiencies can lead to an increase in anterior and rotary instability, which changes the joint's loading pattern creating subsequent secondary damage to the surrounding structures (22). Such secondary damage to the chondral structures has been linked to the development of PTOA. However, this does suggest that there is a need to limit and prevent the long-term consequences of ACL injuries with a view to optimising long term joint health.

Post-injury, patients are offered either a surgical or conservative management pathway. The outcomes of each approach vary depending on the patient and their presentation, but both are optimised by early detection and early intervention. Surgically this seeks to improve the structural integrity of the knee; conservatively this seeks to improve the neuromuscular control and mechanics of functional movements to compensate for the structural loss. Although there is no evidence that a reconstruction reduces the chance of PTOA, compensatory changes to knee biomechanics and tibiofemoral contact patterns acutely post ligament injury significantly expedite the progression in metabolic changes which are associated with the development of arthritis (25). If the time between injury and diagnosis is shortened and appropriate management strategies accessed, abnormal biomechanical patterns and intra-articular inflammatory markers can be minimised. A shorter healing process and reduced stress to surrounding knee structures has the potential to reduce the effects of PTOA and optimise care for this patient group. Thus, there is a need for faster access to the relevant surgical or conservative management strategies as this will lead to economic and health benefits as well as enhancing the patient experience and health outcomes (10, 26).

2.10. Evaluating the Diagnostic Pathway for Acute ACL Injuries in Trauma Centres: A Systematic Review

2.10.1.1. Publication

The contents of this section were published as a systematic review in the BMC musculoskeletal; a copy of this publication can be found in Appendix A: Full Published Systematic Review. Due to this, there may be some repetition in the previous chapter.

2.10.1.2. Introduction and Aims

The systematic review aimed to scope the clinical assessment methods and associated timeframes within the diagnostic process for ACL injuries. This provided an overview of the current pathway options this patient cohort faces; it unveiled the healthcare system's successes and failures within this care pathways and identified potential improvement strategies.

2.10.2. Background

Most acute ACL injuries present to trauma centres, such as A&E departments and minor injury units (2, 38, 60). In the immediate acute injury phase, joint effusion and muscular compensation are barriers to assessment (38, 61). ACLs are well known to be accompanied by joint swelling, which is postulated to reduce diagnostic accuracy to 12.7% (61). Swelling, in any joint, is comprised of painful inflammatory markers, which can lead to joint stiffness and painful movement (62). Assessment of the joint requires passive joint manipulation to induce stress on these ligaments to test for their integrity, but in patients with acute swelling and pain, this causes an involuntary muscle-guarding response which can prevent the assessor from inducing the appropriate level of stress on the ligamentous structures.

Since ACL injuries most commonly present to A&E, where assessment techniques are hindered by the initial inflammatory response, it is important that initial assessments are accurate. Clinical assessment methods, whilst low cost, are subject to significant errors; diagnostic accuracy can be as low as 56% (35). A paper published in 1996 stated diagnosis takes on average 21 months (63), a more recent paper exploring the assessment of ACLs in the emergency department concluded there has been little improvement since then, with only 14.4% of ACL injuries diagnosed at initial presentation (35).

Emergency physicians are known to have poor diagnostic accuracy, it can be as low as 25.9%, compared to more experienced professionals such as sports medicine physicians when assessing acute ACL injury (38, 64). However, Perera's study emphasised that even with specialist training, orthopaedic physicians missed diagnosis in 28% of patients (38). This reinforces that clinicians cannot ensure diagnostic accuracy with the current clinical assessment methods (38), thus emphasising the need for more accurate diagnostic tests at acute trauma centres to improve patient outcomes (64).

Understanding current assessment methods and diagnostic pathways for patients with acute ACL tears is paramount to developing more efficient diagnosis recommendations and assessment measures. Thus, we sought to systematically review the literature for assessing patients with suspected ACL tears who come in through the emergency department, with a view to defining current practice.

2.10.3. Methods

2.10.3.1. Search Strategy

The databases MEDLINE, EMBASE, and CINAHL were used to conduct the search and published articles up until the 25th of May 2021 were eligible for inclusion in the review. The search terms were either classed as headings or keywords. The Boolean search strategy was used to appropriately combine the terms and retrieve the most relevant articles [Table 1]. 'ACL' AND 'trauma centre' were the two topic headings, all keywords and subject headings within the topic heading 'ACL' were combined with 'OR', this was repeated with the keywords and subject heading within the topic heading 'trauma centre'. Topic headings were then combined with 'AND'. After the automated search using the terms listed in [Table 1], a hand search was undertaken which cross-referenced the terms in [Table 1] against the bibliographies of the relevant articles, to check no key terms had been missed.

Table 1: Boolean Search Strategy

Topic headings	Keywords	Subject headings	
ACL	ACL OR anterior cruciate Adj2 ligament OR anterior adj2 cruciate ligament	MEDLINE	Anterior cruciate
		EMBASE	ligament/
			Exp Anterior cruciate ligament rupture/
			Exp Anterior cruciate ligament injury/

		MEDLINE OVID	Anterior cruciate ligament/
		EBSCO CINAHL	MH "anterior cruciate ligament"
Trauma center	Emergency department* OR emergency health service* OR emergency adj2 accident OR first contact practitioner* OR casualty OR triage* OR delay adj2 diagnosis OR late* adj1 diagnos* OR orthop?edic clinic* OR knee clinic* OR Emergency ward*	MEDLINE EMBASE	Emergency ward/
			Exp emergency health service/
			Delayed diagnosis/
		MEDLINE OVID	EXP Emergency medical services/
			Delayed diagnosis/
		EBSCO CINAHL	MH "emergency medical services+"
			MH "diagnosis, delayed"

2.10.3.2. Eligibility Criteria

The review scoped the current assessment methods and diagnostic pathways for ACL injury in the emergency department (ED) for patients. For articles to be eligible for the systematic review, they had to meet the following inclusion criteria: the assessment had to be completed in an Emergency Department, the injury was acute on initial assessment (within 6 weeks), at least one clinical assessment tool was stated, and participants were deemed to have sustained an ACL injury. Articles were excluded if: participants had experienced a previous ACL injury, participants had known chronic joint deformities (such as osteoarthritis), animals

or cadavers were included within the sample, the paper was not available in English, and if participants were under the age of 18. Study designs that were case reviews, case studies, or series were also excluded.

2.10.3.3. Selection Process

All articles identified from the search from the databases were exported to a reference manager software called Endnote X20 (Clarivate Analytics, Philadelphia, PA, USA). Duplicates were removed, and all references were then exported to Covidence (Veritas Health Innovation, Melbourne, Australia). Articles were first screened by text and abstract, those that were deemed relevant underwent a full-text review. The articles were screened against the inclusion-exclusion criteria by two independent reviewers (PhD candidate and Main Supervisor), and discrepancies between reviewers were then resolved by discussion.

Studies that included participants under the age of 18 were contacted asking for data specific to the population of interest. A few articles did not specify whether the injury was acute or chronic, thus the authors of these articles were contacted for further information.

2.10.3.4. Data Extraction

The following data were extracted from the selected articles: aim; sample size; study design, time since injury, participant number, clinical assessment tool, reference standard, assessing clinician (profession and experience), time to reach diagnosis, the median number of appointments to reach diagnosis, the meantime to await surgery and diagnostic accuracy.

2.10.3.5. Quality Appraisal

The QUADAS-2 checklist [Table 2] was the quality appraisal assessment tool used to assess papers. The QUADAS-2 is widely used for studies evaluating diagnostic accuracy assessment measures. It is made up of 4 domains: patient selection, index tests, reference standards, and flow and timing. As shown in Table 2, the first 3 domains are split into assessing sections A and B, A) risk of bias, and B) concerns regarding applicability. The 4th domain: flow and timing, did not include section B. The sections were comprised of signalling questions [Table 2] that would ultimately determine the 'risk of bias' and 'concern regarding applicability'. The QUADAS-2 is not designed to give an overall quality score, instead, it provides an overall judgment on the two assessment criteria. If a paper had more than one signalling question

that was 'at high risk' (X) it was regarded as 'at risk of bias', the 'concern regarding applicability' was then assessed.

Table 2: Signalling questions for QUADAS-2 quality assessment

Signaling questions for QUADAS-2 quality assessment	
Domain 1: patient selection	
A: risk or bias	Was a consecutive or random sample of patients enrolled?
	Did the study have appropriate exclusions?
	Was the study retrospective?
	Was a sufficient sample size used?
	Could the selection or patient have introduced bias?
B: concerns regarding applicability	Are there concerns that the included patients do not match the review question?
Domain 2: index test(s)	
A: risk or bias	Were the index test results interpreted without knowledge of the results of the reference standard?
	Were all the index tests specified and clearly explained?
	Could the conduct or interpretation of the index test have introduced bias?
B: concerns regarding applicability	Is there concern that the index test, its conduct, or interpretation differ from the review question?
Domain 3: reference standard	
A: risk or bias	Is the reference standard the 'gold standard' for ACL diagnosis?
	Were the reference standard results interpreted without knowledge of the results of the index test?
	Could the reference standard, its conduct, or its interpretation, have introduced bias?
B: concerns regarding applicability	Is there concern that the target condition as defined by the reference standard does not match the review question?
Domain 4: flow and timing	
A: risk of bias	Was there an appropriate interval between the index test and the reference standard?
	Was the time frame defined where the initial consultation (index test) and/or reference standard was completed? /Unclear
	Did all patients receive a reference standard?
	Did all patients receive the same reference standard?

	Were all patients included in the analysis?
	Could the patient flow have introduced bias?

2.10.4. Results

A total of 673 articles were initially obtained across all three databases. After duplicates were removed, 353 articles were included for screening, and 64 articles were eligible for a full-text review after title and abstract screening. Fifty-eight of the articles had contained one or more of the exclusion criteria as stated in 2.10.3.2. Following this, six articles were identified as being appropriate for inclusion, Figure 1 details the PRISMA diagram and the reasons for article exclusion at each stage.

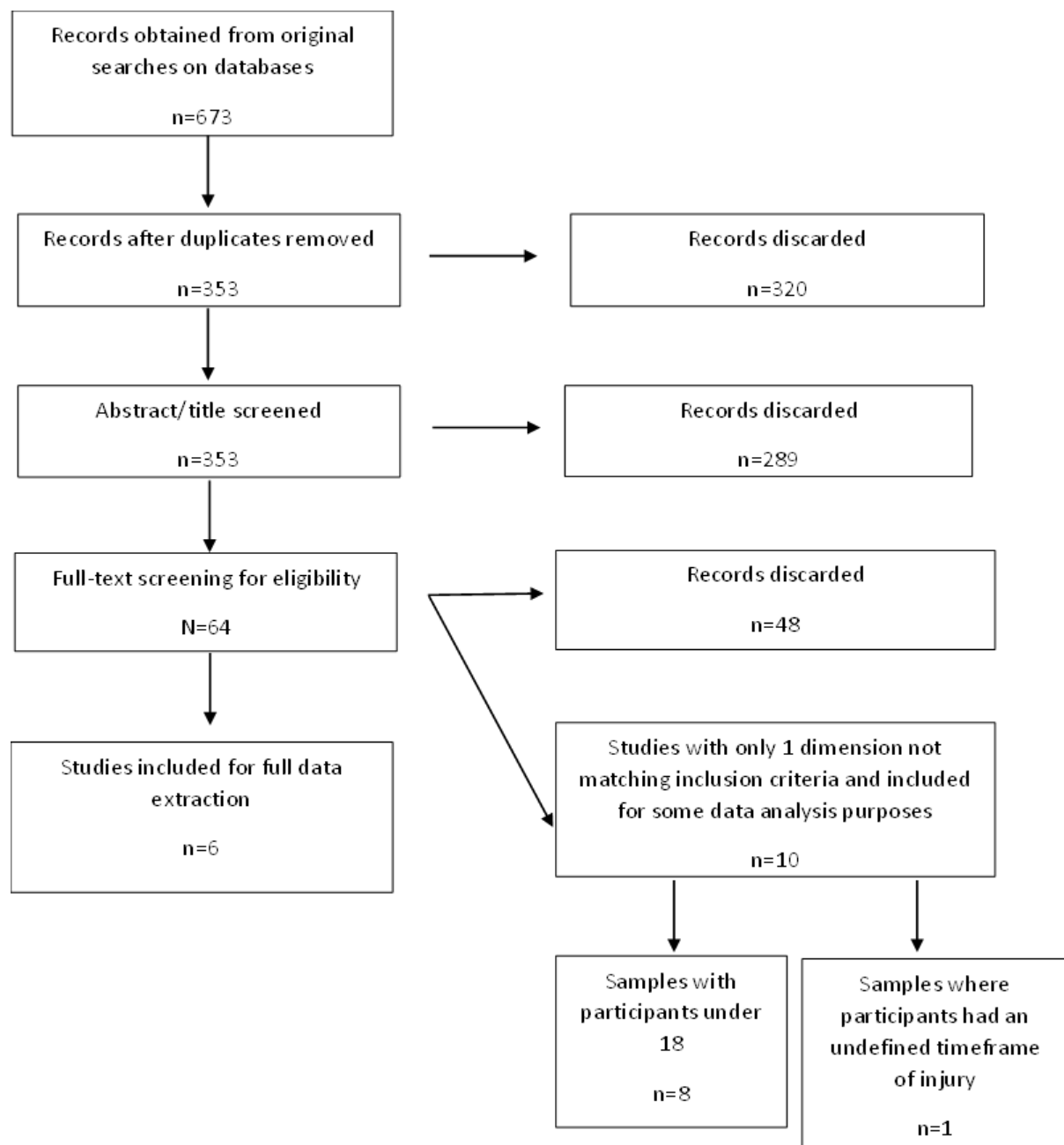


Figure 1: PRISMA Diagram Detailing the Selection Process

2.10.5.1 Main Characteristics of Included Studies

Table 3 details the main characteristics of the studies included. All studies used a consecutive sampling method, however, the articles varied in sample size, methodology, and study design, including both prospective and retrospective studies.

The study completed by Clifford et al (2) included participants with injuries that were outside of the acute timeframe (6 weeks), authors provided raw data for all participants and only the data of those who matched the inclusion criteria (61/82) were included in this review.

Table 3: Main Characteristics of Included Studies

Author (Date)	Article title	Journal	Aims	Participants (n)	Protocol
Ball et al (2010)	The impact of an Acute Knee Clinic	Annals of the Royal College of Surgeons of England	Evaluate the impact of an acute knee clinic on diagnosis and treatment for acute knee injuries	100	Design: - Prospective study - Consecutive sampling Methods: - Audit or timeframes and assessment process
Clifford et al (2021)	Acute knee clinics are effective in reducing delay to diagnosis following anterior cruciate ligament injury	Knee	Investigate the impact of an acute knee clinic compared to the standard A&E pathway	61	Design: - Prospective study - Consecutive sampling Methods: - Physical examination - Imaging - Arthroscopy
Hardy et al (2017)	The use of history to identify anterior cruciate ligament injuries in the acute trauma	Emergency Medicine Journal 2017	To investigate what clinical history features indicate ACL injuries	194	Design: - Prospective study - Consecutive sampling Methods:

	setting: the 'LIMP index'				• Survey • Questionnaire • Physical examination • Imaging
Lee and Yun (2019)	Feasibility of point-of-care knee ultrasonography for diagnosing anterior cruciate and posterior cruciate ligament tears in the ED	American Journal of Emergency Medicine 2019	To evaluate the use of ultrasound compared to MRI to diagnose ACL injury	62	Design: • Prospective study • Consecutive sampling Methods: • Physical examination • Imaging
Parwaiz et al (2016)	Anterior cruciate ligament injury: A persistently difficult diagnosis	Knee	To investigate if there has been an improvement in ACL diagnosis over the last 20 years	160	Design: • Retrospective design • Consecutive sampling Methods: • Retrospective data extraction
Wang et al (2016)	Efficacy of knee joint aspiration in patients with acute ACL injury in the emergency department	Injury 2016	To evaluate the impact of joint aspiration on the sensitivity of joint laxity tests on patients with ACL injuries through the emergency department	60	Design: • Retrospective design • Consecutive sampling Methods: • Retrospective data extraction • Physical examination • Imaging

2.10.4.1.1. Article Quality

The QUADAS-2 showed variation between studies [Table 4]. The risk of bias in domain 1 (Patient Selection) was high for 50% of the articles (11, 12, 15), those that scored low were either due to an insufficient sample size, an absence of power calculations, inappropriate exclusion criteria, or a retrospective design including only patients who underwent arthroscopy. For domain 2 (Index test), two of the studies were not explicit when describing their assessment methods, thus negatively affecting the risk of bias, and resulting in an unclear concern regarding applicability (11, 15). In domain 3 (reference standard), the article that was at high risk of bias (3) completed a clinical assessment as their 'reference standard' which is not the gold standard for ACL injury diagnosis, whereas another study's (15) risk of bias was unclear as the reference standard was not clearly stated. Domain 4 (flow and timing) appeared to be the poorest across all the studies, many articles (11, 12, 15) did not define the time frame between the index test and the reference standard. In addition, participants in two studies did not use a consistent reference standard (13, 15). Figure 2 and Figure 3 represent the percentage of articles scoring high, low, and unclear for each domain.

Table 4: Quality Assessment of Included Studies

STUDY	RISK OF BIAS				APPLICABILITY OF CONCERNS		
	Domain 1: PATIENT SELECTION	Domain 2: INDEX TEST	Domain 3: REFERENCE STANDARD	Domain 4: FLOW AND TIMING	Domain 1: PATIENT SELECTION	Domain 2: INDEX TEXT	Domain 3: REFERENCE STANDARD
Ball et al 2010	X	X	?	?	✓	?	?
Hardy 2017	✓	✓	X	X	✓	✓	✓
Lee and Yun 2020	✓	✓	✓	✓	✓	✓	✓
Wang 2016	X	✓	✓	?	✓	✓	✓
Parwaiz 2016	X	X	✓	?	✓	?	✓
Clifford et al 2021	✓	✓	✓	X	✓	✓	✓

KEY:

✓ = LOW

X = HIGH

? = UNCLEAR

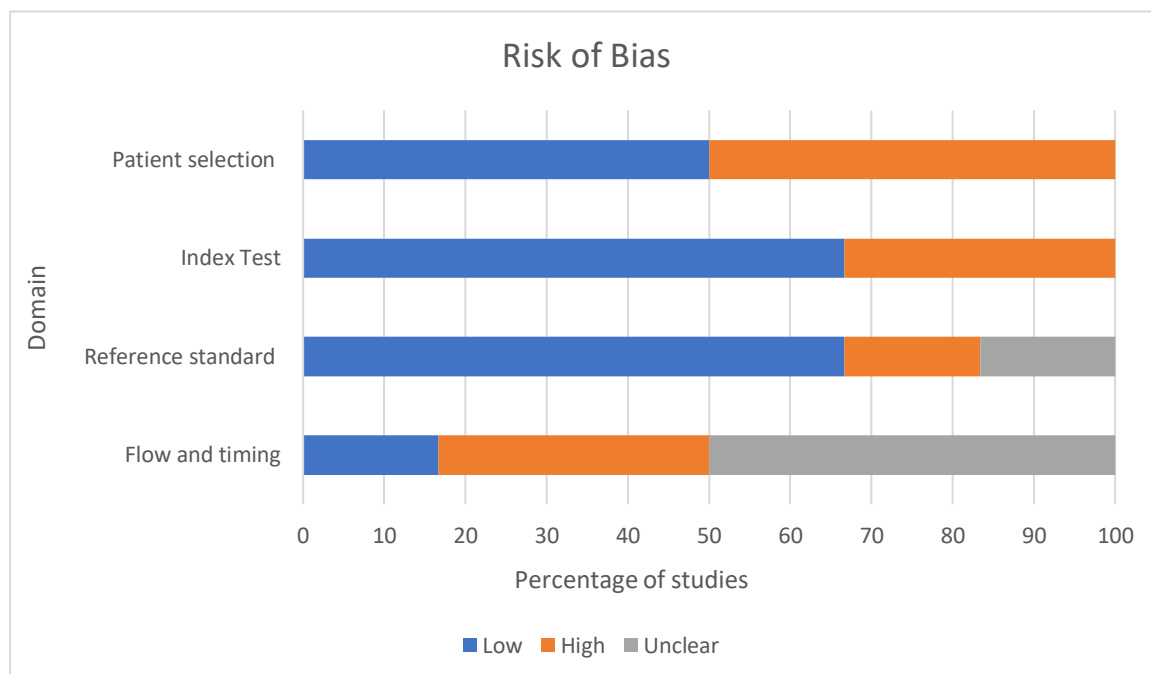


Figure 2: Methodological quality graph summary: Bar chart representing the percentage of studies that are rated low, high, and unclear for domain 'risk of bias'

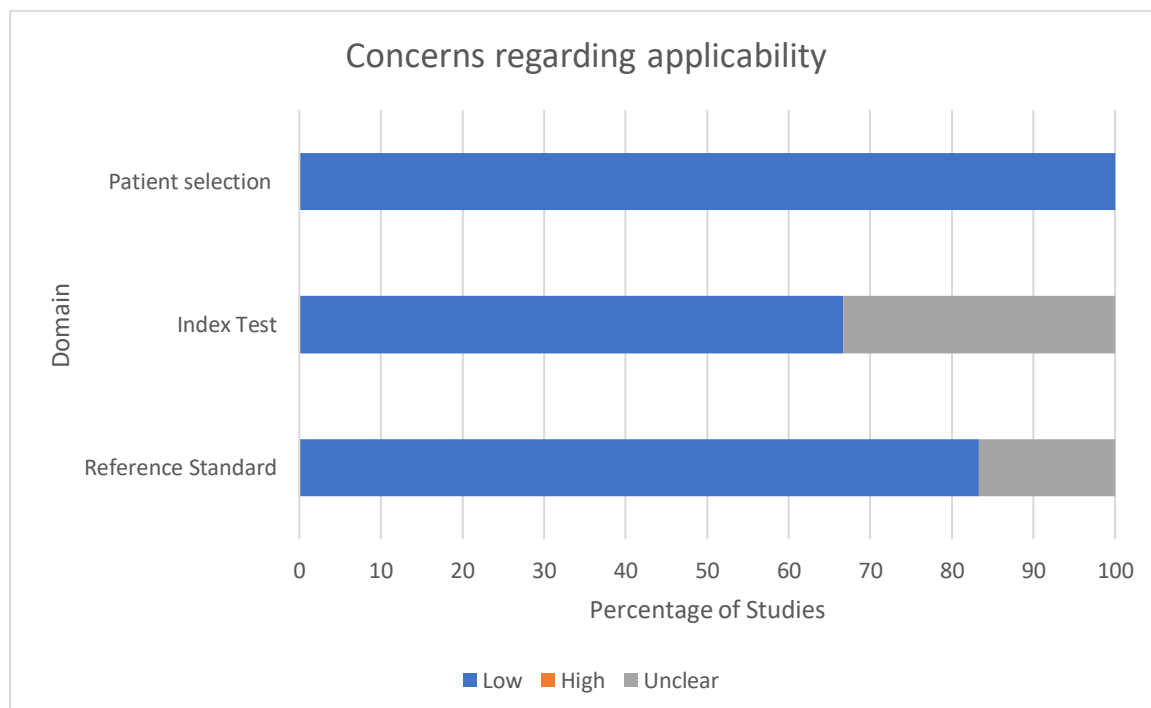


Figure 3: Methodological quality graph summary: Bar chart representing the percentage of studies that are rated low, high, and unclear for domain 'concerns regarding applicability'.

Table 5: Assessment Methods used for included Studies.

AIM	TEST	INDEX TEST	REFERENCE STANDARD
Laxity	Lachman's	(2, 34)	(2)
	INSTABILITY'	-	-
	Lever sign	-	-
	Pivot shift	(2, 34)	(2)
	Anterior drawer	(2, 34)	(2)
	KT1000	-	-
Range of movement	Active range of movement	(34)	-
	Passive range of movement	-	-
Swelling	Time delay swelling	(2)	-
	Joint effusion	(2, 34)	(2)
Functional ability	Weight bear	-	-
	Inability to continue activity	(2)	-
	Gait	-	-
Pain	Palpation	(34)	-
	Temperature	(34)	-
	Joint line tenderness	(34)	-
	Pain	-	-
Imaging	X-RAY	(2)	(2)
	Ultrasound	(65)	-
	CT	-	-
	MRI	-	(2, 60, 65)
Subjective assessment	Mechanism of Injury	-	-
	Lysholms functional score	-	-
	Locking	-	-
	Unspecified clinical history	(35, 60)	-
	Clicking	-	-
	Giving way	(2)	-
	Popping sound	(2)	-
	'LIMP' index	(2, 60)	-
Unspecified assessment	Unspecified clinical assessment	(35, 65)	(60)
	Physicians' agreement	-	-
	Unspecified	(3)	(3, 35)
	Orthopaedic surgeon exam	-	-
Surgery	Anaesthetic eval	-	-
	Arthroscopy	-	(2, 34, 60)

**Corresponding column values are the papers which contained the relative index test and/or reference standard. The paper can be found within the number in the bibliography of this thesis. **

2.10.4.1.2. Index Tests

Table 5 presents the index tests and reference standards used in the studies included in the review. An index test, in this instance, is the initial assessment method(s) used to evaluate the knee. Passive laxity tests such as Lachman's, anterior drawer, and the pivot shift test were used to assess knee instability in two of the articles (12, 13). Lee and Yun (18) used ultrasound

and an unspecified clinical assessment as their index test. Joint effusion was part of the initial assessment in 3 of the studies (3, 12, 13), inability to continue activity was also an injury indicator in two of these articles (3, 13). Another study's index tests comprised of palpation, temperature, and joint line tenderness (2), whilst a different article used X-Rays as a means of ruling out fractures (12). Giving way and a 'pop' at the time of injury were a strong indicator of injury in two of the articles (13). The other two studies left their initial assessment method unspecified (12, 13).

2.10.4.1.3. Reference Standards

A reference standard, in the context of ACL injury, is a verification tool used to measure the accuracy of the respective index test. MRIs were used as a reference standard in many of the studies (3, 13, 18, 19). Whereas, other participants were retrospectively recruited from ACL reconstructive surgeries, leaving arthroscopy as the designated reference standard (3, 12, 13). In Clifford et al's study (13), only four participants did not have an MRI, of the 61 patients that met the inclusion criteria, 25 were initially diagnosed using MRI alone, another 25 were diagnosed from clinical examination findings, 9 participants diagnoses were confirmed from a combination of MRI and clinical assessments, and 2 had an arthroscopy. Hardy et al (3) verified their index test with either an unspecified clinical assessment, MRI, or arthroscopy. They did not specify which participants had the respective reference standard (3). Some studies did not specify their diagnosis verification, they simply eluded that ACL injury was confirmed (11, 15).

2.10.4.1.4. Time to reach a diagnosis.

Table 6 represents the time taken to reach diagnosis, this varied between studies. Whilst Ball et al (3) reported that before an acute knee clinic was established, it took 123 days for diagnosis to be confirmed, after the acute knee clinic was formed, this was reduced to 14 days. Lee and Yun's participants (65) were immediately scheduled for an MRI after their ultrasound on initial presentation to A&E, they reported that diagnosis took an average of 3.8 days. Hardy et al (60) observed a considerable increase in the delay to diagnosis when follow-ups were not scheduled. Participants who had a follow-up arranged had a delay of 29 days to diagnosis, when the patients who were diagnosed at the initial consultation were removed, the delay increased to 46 days. Participants with no follow-up arranged had a delay of 198 days to diagnosis, when those who were diagnosed at the initial consultation were removed,

this increased to 229 days. Wang et al's (34) participants were all referred to an outpatient department to be seen by professionals in a specialist knee clinic within 7-14 days of initial presentation to the Emergency Department. It was eluded that confirmation of diagnosis was reached at this outpatient visit; patients who had an aspiration performed on initial A&E presentation took 6.7 days to be diagnosed; those who did not took an average of 6 days. Parwaiz et al (35) had 48.8% of the participants present to A&E, of these, only 5% were diagnosed on initial presentation, there was no further data on how long diagnosis took to be confirmed. Clifford et al's data revealed diagnosis took on average 115 days (2).

Table 6: The allocated study reference number for the sub-study components, including sample size, the meantime to reach diagnosis, and the mean number of appointments to reach diagnosis.

Author	Study components	Study reference number	Meantime to reach diagnosis (days)	Sample size	The mean number of appointments to reach diagnosis
Ball et al 2010	Before acute knee clinic (AKC)	1	123	100	5
	Post-AKC	2	14	100	1
Lee and Yun 2020	Ultrasound	3	3.8	62	2
Hardy et al 2017	Follow up arranged	4	29	120	-
	Follow up arranged with initial diagnosis removed	5	46	101	
	No follow up arranged	6	198	43	
	No follow up arranged with initial diagnosis removed	7	229	40	
Wang et al 2016	Aspirated knee group`	8	6.7	18	-
	Non-aspirated	9	6.0	42	
Parwaiz et al 2016	Those presenting to an Emergency Department	-	Not documented – although only 5% reached initially	78	-
Clifford et al 2021	Whole Participant sample	10	115	61	3.3
Meta Mean		11	68.60	-	-

2.10.4.1.5. Statistical Analysis

A meta-analysis of the weighted mean time to reach diagnosis for all the studies was calculated to be 68.60 days [CI 23.94, 113.24] [Figure 4].

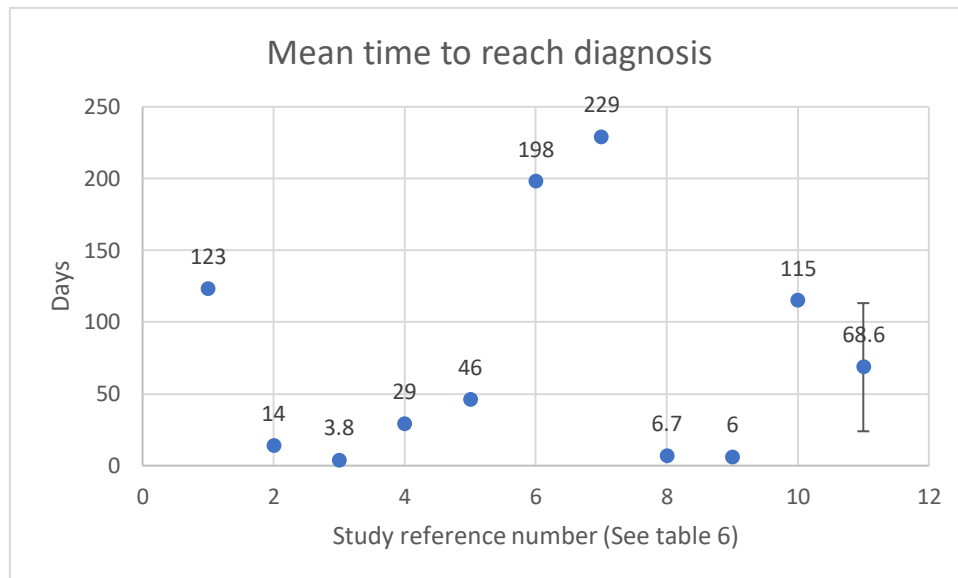


Figure 4: Scatter Diagram showing the 'meantime to reach diagnoses for individual sub-sample groups, and meta mean with 95% confidence intervals (table 6).

2.10.4.1.6. Mean number of Appointments to Reach Diagnosis

Three of the papers reported the number of appointments to reach diagnosis, ranging from 2 to 5 [Table 6]. However, the number of appointments varied depending on the study design, those that only used imaging modalities took less time to reach diagnosis (2 appointments) (18) compared to those that did not (3.3 and 5 appointments) (15) (13).

2.10.4.1.7. Assessing Clinician

Table 7: Assessing Clinician and Delay to Surgery

Author	Assessing clinician		Time until surgery	
Ball et al	Unspecified		196	
	'specialist'		126	
Lee and Yun	Board-certified emergency physician with over 5 years of experience AND specialist MSK radiologist		-	
Hardy et al (time to initial appointment with surgeon)	22 specialists		Follow up arranged	61
			Follow up arranged with initial diagnosis removed	69
			No follow up arranged	328
			No follow up arranged with initial diagnosis removed	311
Wang et al	In the ED	junior orthopaedic surgeon	-	
	In the OPD follow-up	senior orthopaedic surgeon		
Parwaiz et al	advanced nurse practitioner OR A junior ED trainee OR A senior ED trainee		-	
Clifford et al	triaged by an A&E Sister and assessed by an A&E physician	1	-	
	A&E registrar	1		
	triaged by nurses and assessed by an A&E Physician	4		
	normal adult triage route and then assessed by an A&E physician	53		
	adult triage and was then assessed by an emergency nurse practitioner	1		
	orthopaedic doctor	1		

Table 7 displays the assessing clinicians and the time until surgery. Ball et al (3) did not specify the assessing clinician before the acute knee clinic was established, however, all participants were assessed in the emergency department. Patients assessed in the acute knee clinic were seen by a 'knee specialist'. The study by Lee and Yun (65) included a board-certified emergency physician with over 5 years of experience, and an MSK radiologist familiar with ultrasonography and its affiliation with ACL injury. The radiologist trained the emergency department practitioner in sonography prior to the study (65). Hardy et al (60) described the assessor in the acute knee clinic as 'a person highly trained in a particular branch of medicine', 22 were included, some of which were surgeons. Wang et al's (34) initial clinical assessment was performed by a junior orthopaedic surgeon; they were then followed up by a senior orthopaedic surgeon with over 10 years of experience (34). Parwaiz used either an advanced nurse practitioner, a junior emergency department trainee, or a senior emergency department trainee to assess participants (35). Clifford et al (2) used participants that were assessed by a variety of clinicians on initial presentation.

2.10.4.1.8. Time Until Surgery

Not all studies included data about surgery [Table 7]. Ball et al's (15) participants waited on average 196 days (3-48) to receive their relevant surgery before the acute knee clinic was established, this then decreased to 126 days (8-480) afterwards. Hardy et al (3) did not record the surgical waiting times, however, data was published from the time of injury to when participants had their initial appointment with a surgeon. Initial surgical consultation increased when patients were not arranged for a follow-up after their initial consultation. Those who had a follow-up arranged were waiting 61 days (47-80), and those who had a follow-up arranged once patients who received their diagnosis on initial appointment were removed, waited for an average of 69 days (51-93). Those with no follow-up arranged waited an average of 328 days (213-503) and those with no follow-up arranged once patients who received their diagnosis on initial appointment were removed waited for an average of 311 days (210-481).

2.10.4.1.9. Diagnostic Accuracy

Table 8: Showing the accuracy, sensitivity, specific NPV, and PPV of assessment methods. The performance characteristics were dependent on the data available in the articles.

Authors	Diagnostic accuracy						
Ball et al	Unspecified						
Lee and Yun				Ultrasound performer 1 (%)	Ultrasound performer 2 (%)		
	Sensitivity			90.6	96.9		
	Specificity			93.3	90		
	Positive predictive value (PPV)			93.6	91.2		
	Negative Predictive value (NPV)			90.3	96.4		
	Accuracy			91.9	93.6		
Hardy et al	Sensitivity	All 4 facets		57.8%			
		3 facets		83.9%			
		2 facets		95.8%			
		1 facet		99.5%			
Wang et al		Group 1- Aspirated knee (Sensitivity)			Group 2- non-Aspirated knee (Sensitivity)		
		ED	Lachman’s	47.1%	ED	Lachman’s	40.5%
			Pivot shift	11.8%		Pivot shift	9.5%
		OPD	Lachman’s	76.5%	OPD	Lachman’s	47.5%
			Pivot shift	76.5%		Pivot shift	31.0%
		Parwaiz et al		Unspecified			
Clifford et al					Sensitivity		
		Lachman’s			74.5%*		
		Anterior Drawer			61.4%*		
		Pivot Shift			100%*		

*Values were re-calculated from the raw data sent by the authors. Only the population of interest was included in these values. Participants outside of the 6-week timeframe, under 18, or assessed outside of A&E were excluded.

Values of diagnostic accuracy [Table 8] were not available for all studies due to the way participants were recruited. However, they were available for the study performed by Lee and Yun (18), who recorded high accuracy of both ultrasound performers 1 and 2 of 91.9% and 93.6% respectively. Three of the studies only had values of true positive, and false negative cases; the participants that were assessed were of a population of confirmed ACL tears, meaning only sensitivity data was available (3, 12, 13). In order for specificity, accuracy, PPV, and NPV to be calculated, false positive and true negative data must be available (20, 21). Hardy et al.(61) established an acronym called the LIMP index when assessing for ACL injuries, the 4 criteria are leg giving way at time of injury , inability to continue activity, marked effusion, and pop at time of injury. They recorded that 99.5% of participants reported at least

1 facet of the LIMP index, 95.8% reported 2, and 83.9% of participants reported 3, this dropped to 57.8% of participants reporting all 4 variables of the LIMP index (61). Wang et al (12) and Clifford et al (13) both investigated the pivot shift and Lachman's test. The Lachman's had poor accuracy in Wang et al's study when initially performed in the Emergency Department at the time of injury in both the aspirated and non-aspirated cohort (47.1% and 40.5% respectively). This increased to 76.5% in the aspirated cohort when reviewed 2 weeks later in the outpatient department, this value was similar to the sensitivity reported by Clifford et al (74.5%). Values for the pivot shift test varied widely (9.5-100%), the accuracy increased significantly in the aspirated knee group (from 11.8% to 76.5%). Clifford et al's study revealed a remarkable sensitivity of 100%, however, this result was only based on 3 participants. Parwaiz et al (11) did not have any data on the diagnostic accuracy of their assessment methods.

2.10.5. Discussion

The current diagnostic methods and assessment pathways available to patients presenting themselves to an Emergency Department with a suspected ACL injury were evaluated in this systematic review. Although numerous papers investigated diagnostic accuracy for ACL tears, only 6 were identified that assessed acute ACL injuries (less than 6 weeks) in an acute trauma setting.

Of the 6 papers reviewed, many studies had a high risk of bias, this was primarily due to: (a) absence of power calculations, (b) retrospective design (c), unspecified index tests and reference standards, and (d) undefined timeframes between diagnostic tests and verification. Many studies were insufficiently powered or were retrospective in nature. Both factors increase the risk of bias for domain 1. Unspecified index tests and reference standards lead to an inability to assess the risk of bias or concern regarding applicability, thus affecting the quality scores of domains 2 and 3. Domain 4 was negatively impacted by undefined timeframes between the initial assessment (index test), and the diagnostic verification (reference standard). If this is not standardised amongst participants, longer wait times between the index test and reference standard will have repercussions on the recorded accuracy of the assessment method. Consequently, this review has identified many areas for improvement for future studies evaluating diagnostic tests.

A reoccurring theme in the literature is that the time to reach a diagnosis is reliant on a thorough assessment at initial presentation, which is not always guaranteed in current clinical practice. Laxity tests are commonly performed and often accompanied by a subjective assessment and a history of the mechanism of injury. A reported pop at the time of injury, an inability to continue activity, a history of giving way, and joint effusion are common subjective markers of ACL injury, however this alone is not enough to diagnose injury. Without robust objective findings of laxity, clinical diagnosis of ligamentous injury remains inconclusive. Joint laxity can be difficult to provoke in many circumstances, but this difficulty is increased when inexperienced assessors are presented with an acutely swollen knee (9, 34, 35). Whilst swelling alludes to a high suspicion of an ACL tear, it is a barrier to accurate assessment, as demonstrated by Wang et al (34). The authors theorised that aspiration reduces Substance P within the joint, which consequently decreases pain and prevents the patient from 'guarding' during joint laxity tests (34). Whilst an interesting finding, point of care aspiration is not widely performed, this is due to the novelty of this research as well as the required expertise to perform this procedure, and the associated risk of joint infection. Further research should be conducted on this patient cohort to explore the associated patient benefits and risks of joint aspiration in suspected ACL injuries. The reliance on robust assessment methods at initial presentation indicates a greater need for a recognised, consistent triaging approach amongst non-specialist departments, in order to reduce prolonged and false-negative diagnoses.

Radiological methods, such as ultrasound and X-rays (46, 66) are popular radiological assessment methods. Ultrasound allows for fast comparison to the contralateral limb and is not subject to lengthy waitlists (46). Its advantages are that it allows for the real-time visualisation of soft tissue without the use of radiation. However, diagnostic MSK ultrasound is not routinely used in the Emergency Department due to the lack of available specialists (46). X-Rays are used as an assessment adjunct to rule out bony pathology, whilst they do not rule in or out ligamentous injury, they act to check bony alignment and health in case emergency orthopaedic involvement is needed.

Nearly all studies used either MRI or arthroscopy to verify injury (5, 29, 30, 46-49) and these were the most popular assessment verification method (19, 32, 33, 38). The ability of both methods to assess the morphology of soft tissue means that they are considered gold standard diagnostic approaches (1, 50), many clinicians will only confirm a diagnosis on their

completion (33, 38), suggesting that many healthcare professionals are not confident in confirming diagnosis based on clinical assessment alone.

When performed by a specialist clinician, the diagnostic performance characteristics of laxity tests increase significantly (32) this is reflected by the inconsistencies amongst pivot shift test sensitivity (9.5-100%) (32, 33). Although Clifford et al reported 100% sensitivity (33), this test was only performed on 3 participants (out of 61), all of which were completed by a consultant orthopaedic surgeon which is not reflective of acute settings assessments. Diagnostic rates during initial assessment within the emergency department are reported as low as 5% (31), as previously mentioned, this is attributable to a lack of experience and an unconfident skill set. As a result, patients who are deemed at risk of ACL injury are triaged to specialist practitioners. This triaging pathway ensures a more accurate assessment; however, this relies on the appropriate identification of these patients by Emergency Department clinicians.

Although the findings of this paper reflect that the diagnostic accuracy of clinical assessments have high degrees of variability [Table 8], it is important to note that diagnostic accuracy of clinical assessments has been reported consistently high in other papers (25, 39, 67, 68). However, these findings are based on injuries that are no longer in the acute time frame (25, 39, 68), thereby reducing several of the issues associated with acute assessment (2, 34, 38). In addition, the clinicians performing these assessments are often highly experienced in assessing acute knee injury (39) and were reported in a primary or secondary care setting, or they were performed under anaesthesia (25, 68, 69); these factors are not surprisingly reflected in the higher diagnostic accuracy values.

The term 'diagnostic performance characteristics' is an umbrella term for aspects of diagnostic accuracy. The calculations consist of equations based off false and true positives and negatives which can be found in Section 2.7. False positives and false negatives are the two obstacles within acute MSK injury assessment, if assessment criteria are too rigid and specific, false negatives occur; patients are discharged without the ACL injury identified (2, 48), which can result in a protracted diagnostic pathway with repeated admission and consultations. Contrary to this, if assessment criteria are too comprehensive, although accuracy may be high, false-positive diagnoses will also be in abundance, thus encompassing many other differential diagnoses and overwhelming the service; a prime example of this is Hardy et al's LIMP index (61).

This systematic review yielded an average time frame to reach diagnosis of 69 days, the varied time periods to reach a diagnosis are attributable to the differences in the study design and the assessing clinician. This mean value however is not necessarily representative of clinical practice. Diagnostic performance characteristics were highest in the studies using ultrasound and joint aspiration (34, 65), which is unsurprising due to the expertise required to undertake this assessment.

There is a clear correlation between faster diagnoses and more efficient diagnostic pathways. Those with clinical follow-ups arranged reached diagnosis in a shorter period (3, 34, 61). Lengthy diagnoses were a consequence of prolonged referral times between initial assessment and a specialist review, resulting in multiple appointments before a diagnosis is reached (3)[Table 6]. This is secondary to ineffective initial assessments and subsequent false negatives on clinical testing. The effects of lengthy diagnosis are exposed over time, ACL tears give rise to rotational instability and varus thrust, those with a varus thrust have a 3-fold increase in developing osteoarthritis, furthermore, those with defined OA are often ACL deficient or severely dysfunctional (70, 71). Late diagnosis leads to delayed surgical review (3, 61), as illustrated in [Table 7]. Receiving the appropriate management, whether surgical or conservative, aims to prevent "giving way" and to correct gait abnormalities. Which in turn, prevents subsequent injury deterioration and development of PTOA. Faster, more accurate diagnostic pathways therefore are imperative for improved patient outcomes.

2.10.6. Systematic Review Limitations

Limitations must be considered when analysing the review. Some of the included papers had high risk of bias, thus affecting the evidence of conclusions. Most of the data outcomes showed heterogeneity, subsequently, a meta-analysis could not be completed. The time to reach diagnosis is hard to definitively timestamp, clinical impressions and working diagnoses are often made early, the question therefore arises: when is diagnosis definitively reached? Also, it must be considered that the 'time taken until surgery' was noted as an outcome for 2 of the studies, this is not representative of the conservative management group; complexities arise when trying to define a point in time to represent delayed diagnosis within this patient group. The knee is the most injured joint in sport, with 90% of knee injuries involving the ACL (30). This study only reflects a small proportion of these, more reviews like this must be undertaken for more data to be available and represented in this area. However, it must be

recognised that the lack of publications in this area is a consequence of the adversities in setting up trials in acute settings and phases of injury. Finally, excluding participants under the age of 18 reduced our sample size, though this was appropriate for this review as this was only considering those who are skeletally mature and within an adult healthcare pathway, further reviews into the paediatric population would be of use to evaluate repercussions of late diagnoses in the younger population.

2.10.7. Summary

Clinical tests are highly subjective in assessing acute knee injury. A&E clinicians are often not proficient in performing joint laxity tests which form an integral part of identifying ACL injury, errors in clinical judgement can lead to inappropriate triaging of patients and consequential delayed diagnosis. Radiological verification through MRI is accurate but it is unfeasible to attain an MRI for all those who suffer an acute knee injury due to the high-cost associations and accessibility to MRI scans.

ACL tears cause inherent joint instability, if appropriate management is not sought in an appropriate timeframe it can lead to an increased risk of structural damage to the ACL itself or neighbouring knee structures as well as increasing the chance and expediting the progression of PTOA. A reliable method for joint laxity quantification could help provide objective measures of this subjectively measured assessment method, further research should begin to investigate methods of laxity quantification in order to improve diagnostic pathways, immediate patient outcomes and tackle the repercussions of delayed diagnoses.

3 Obstacles and Discrepancies in ACL Assessment and Management: A Survey of Clinicians

3.1 Introduction

Musculoskeletal (MSK) complaints make up 30% of primary care consultations in the UK (72), with acute knee injuries accounting for approximately 8% of all acute injuries seen in A&E (73). The traditional semi-subjective clinical assessment techniques are subject to significant error margins, which have a negative effect on diagnosis and treatment. There are several common presentation findings that can hinder the diagnosis of an ACL injury including joint effusion and muscular compensation. Acutely post injury, the classical presentation of a patient with a suspected ACL injury, is a large volume of swelling within the joint which makes clinical laxity tests difficult to perform accurately and effectively.

Delayed diagnosis can have implications on knee health and subsequently the person's quality of life (4, 35, 74), increasing the need for more extensive surgical or conservative interventions (35, 75). With up to 50% of ACL tears leading to post-traumatic osteoarthritis (PTOA) (76), this warrants consideration. Thus, whilst there are economic and health benefits in earlier surgical or conservative interventions (35, 74), this can only be realised by improving the speed and accuracy of the initial diagnosis.

This study aims to examine current practices in the diagnosis and management of ACL injuries. By reviewing existing protocols and identifying common obstacles and challenges within both assessment and management pathways, it highlights areas in need of improvement. This section presents an overview of the survey administered to clinicians involved in treating ACL injuries. Understanding these care pathways is crucial for identifying opportunities for service enhancement and determining where an early diagnostic tool could be effectively integrated. Although this survey has not yet been published, it is intended to be developed into a research article and submitted for journal consideration upon completion of the PhD.

3.1.1 Study Rationale

Studies have highlighted that the subjectivity of the current clinical assessment methods means that more experienced and specialised clinicians correlate with a higher diagnostic accuracy.

This study seeks to survey a range of clinicians involved in the management of knee injuries with respect to their decision making and assessment of the acutely injured knee. The purpose of this is to evaluate discrepancies between individuals and compare it to current best practice and recent publications in relation to ACL diagnosis.

3.1.2 Research Questions

What are the key factors influencing clinicians' decision-making in the assessment, referral pathways, and management of acute ACL injuries?

How confident are clinicians in their assessment?

What discrepancies exist in clinicians' assessment and management approaches to ACL injuries?

3.1.3 Study Objectives

- Collate a benchmark of clinical practice with respect to the diagnosis and management of acute ACL injuries.
- Evaluate for similarities and discrepancies between clinicians to allow for data evaluation between
 - Profession
 - Experience
 - Clinical setting

3.2 Methods

3.2.1 Study Design

An online survey was designed to capture clinicians' decision-making processes and clinical rationale for managing this patient group. The survey also assessed the urgency with which clinicians ordered and performed further diagnostic tests.

The survey link included a participant information sheet that provided details about the study. After reviewing this information, participants were asked to provide their consent before completing a series of questions. The survey took no longer than 15 minutes to complete.

3.2.1 Participant Recruitment

Participants were recruited via social media and email circulation through colleagues across various health boards in the UK. Professional organisations including the Chartered society of

Physiotherapy (CSP) and the British Orthopaedic Association (BOA) also assisted recruitment by circulating the study on their websites and social media pages. This study sought to recruit 50 participants from a mixture of professional backgrounds and with a range of experiences in acute knee injury assessment.

3.2.2 Inclusion Criteria

Inclusion criteria included autonomous healthcare professionals such as: Advanced nurse practitioners, junior doctors, senior orthopaedic speciality doctors including senior house officers, registrars and consultants and physiotherapists or any other clinician whose work involved assessing acute knee injury. This could be within an MSK, orthopaedic, fracture clinic, front door streamline service such as A&E, that have a role in triaging and assessing for acute MSK injury.

3.2.3 Exclusion Criteria

- Students
- Non-clinicians
- Those who do not have the autonomy to complete assessments and refer onwards to senior professionals or further investigations.

3.2.4 Withdrawal Criteria

All participant's data was collected anonymously. On completion of the survey participants were not able to withdraw from the study as there will be no way to identify their answers. However, if they decided they did not want to continue the survey mid-completion, they could exit the survey and their results were not included.

3.2.5 Summary of Survey Questions

(See Appendix B: Survey for clinicians assessing patients with suspected ACL tears. for full survey template):

1. What is your professional title?
2. What is your speciality? (If you are rotational or junior staff please state accordingly)
3. What is your primary place of work?
4. In your place of work, what setting do you work in?
5. How many years of experience do you have assessing acute knee injury?

6. If a patient came in with an acute knee injury, what subjective questions would you ask them to rule out or consider an ACL injury?
7. If a patient came in with an acute knee injury, how would you prioritise the following clinical assessment methods, in order to rule out or consider an ACL injury?
8. How confident are you that you could 'feel' for instability and make appropriate conclusions?
9. Who would you refer this patient on to if you were suspicious of an ACL injury?
10. If a patient presented with an acute knee injury, prioritise the following imaging modalities you would want to assist your assessment?
11. Would you consider bracing? If so what brace, and for how long?
12. What advice would you give a patient that was highly suspicious of an ACL injury?
13. Please upload any patient advice leaflets/documents you would provide to where you are suspicious or have diagnosed and ACL injury.

3.2.7 Data Analysis

Survey responses were analysed using descriptive statistics. This analysis was completed using excel, where appropriate tabulations and graphs were derived from the survey questions. Question 12 was asked as an open question type, where results varied, this question was retrospectively divided into 3-subquestions so appropriate descriptive analyses could be made.

A thematic approach was used to assess the open question, where themes and codes were identified for each participant's answer. Using the 4 themes identified a 2x2 frequency table was constructed and a heat map was created to identify relationships and commonalities within each theme.

3.3 Results

3.3.1 Descriptive Statistics

A total of 29 participants completed the survey, 18 were physiotherapists, 10 were doctors at different seniority and speciality levels, and 1 was a nurse.

All clinicians regularly assessed acute knee injuries and most deemed themselves 'specialists' in this area. Out of the 29 participants, 23 worked primarily in the NHS, 5 worked primarily in sport and 1 worked in a private MSK/orthopaedic clinic. Within participants respective work

sites, 11 worked in a general MSK clinic, 6 worked in a soft tissue injury clinic, 2 worked in A&E, 2 worked pitch-side in sport, 1 participant worked in an acute knee clinic, 1 worked in fracture clinic and 1 worked in a private MSK clinic; 5 participants listed “other” of which consisted of a combined role in many settings [Figure 5]. On average, participants had 5.20 (3SF) +/- 6.25 years of experience in assessing acute knee injury.

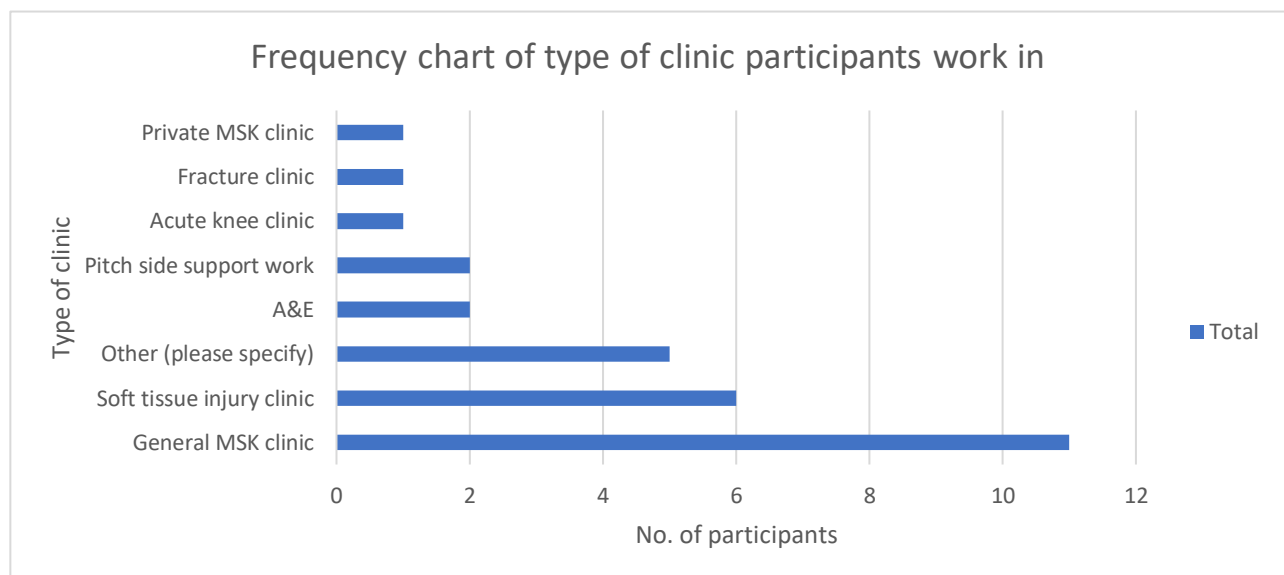


Figure 5: Frequency Bar Chart Representing the Workplace Clinical Setting of Participants.

When asked to rank subjective history criteria when assessing for ACL [Table 9], the following priority order was established: mechanism of injury, pop/snap, giving way, inability to WB after injury, ROM deficiencies, pain, changes in gait and locking. Similarly, when asked to rank objective assessment criteria when assessing for ACL injury the following priority order was established: effusion assessment, Lachman test, anterior drawer test, pivot shift test, AROM, PROM, gait analysis, functional movement assessment, palpation, and strength testing. Of note, despite ranking tests of instability as being important to the assessment of injury, only 24% of participants felt ‘very confident’ in their assessment of knee instability, 69% felt ‘somewhat confident’ and 7% of specialists felt ‘somewhat unconfident’; 1/3 of clinicians’ subsequently did not feel confident diagnosing an ACL tear from their assessment. When asked to rank the imaging method in order of importance if suspicious of an ACL injury, the overall priority positions were X-Ray, followed by MRI and then Ultrasound.

Table 9: Clinician Ranking Positions of Subjective and Objective Assessment Criteria for ACL Assessment

Overall ranking position	Subjective criteria	Objective Criteria
1	Mechanism of injury	Effusion assessment
2	Pop/snap	Lachman
3	Giving way	Anterior drawer
4	Inability to WB after injury	Pivot shift
5	ROM deficiencies	PROM
5	Pain	AROM
7	Changes in gait	Gait analysis
8	Locking	Functional Assessment
9	-	Palpation
10	-	Strength Testing

All participants were asked who they would refer the patient onto if they were suspicious of an ACL injury, 25% would refer to an acute knee clinic, 21% would ask for a surgical opinion, 16% would refer to physiotherapy, 15% would refer to a soft tissue clinic, 12% listed 'other' and 10% chose 'fracture clinic' [Figure 6].

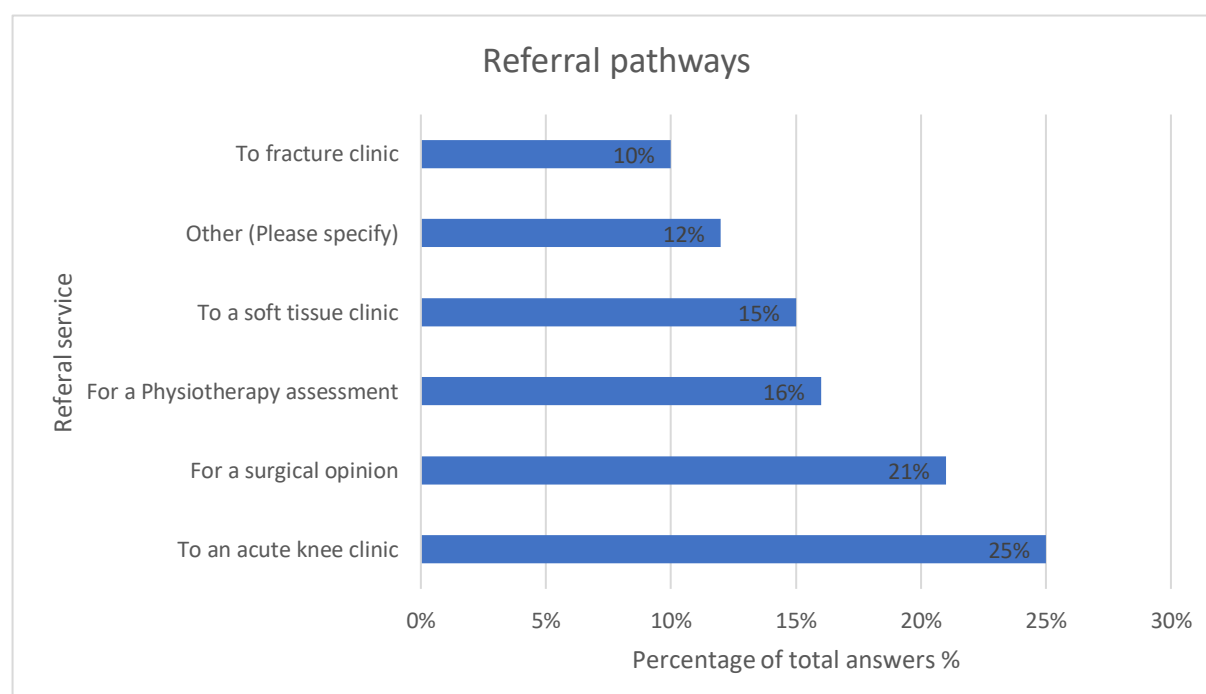


Figure 6: Referral service for ACL injuries

Participants were then questioned about their management of an acute ACL injury. Participants were canvassed on their views on bracing including “Would you consider bracing? If so what brace and for how long?”, as the question has 3 separate parts to it, results were analysed as the respective sub question: ‘would you consider bracing?’, ‘which brace?’ and ‘how long would you brace for?’. Thirty Four percent of participants would brace, 10% said definitively ‘no’, 31% stated maybe, whilst 21% chose ‘If in combination with other knee injuries’, 3% did not specify a response.

Regarding the type of brace used, the majority of participants did not specify (48%), 31% chose they would prescribe a ‘full extension/cricket pad splint followed by a hinge brace’. 10% would use only a hinge brace and 10% clicked ‘none’ [Figure 7]. Again, when asked how long participants would brace the acutely injured ACL, 48% of participants did not specify, 3% stated ‘one week’ 7% listed ‘2 weeks’, 17% chose ‘<6 weeks’, 10% braced for 6 weeks, 3% chose 12 weeks and 10% would not brace [Figure 8].

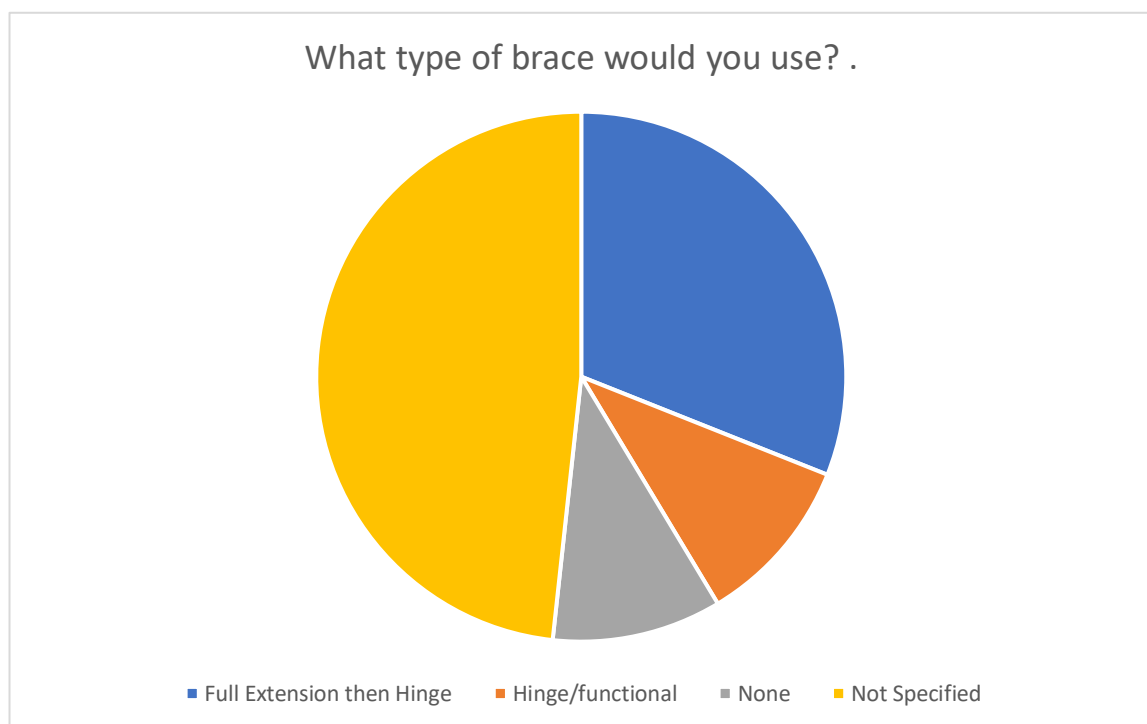


Figure 7: Type of bracing for ACL injuries

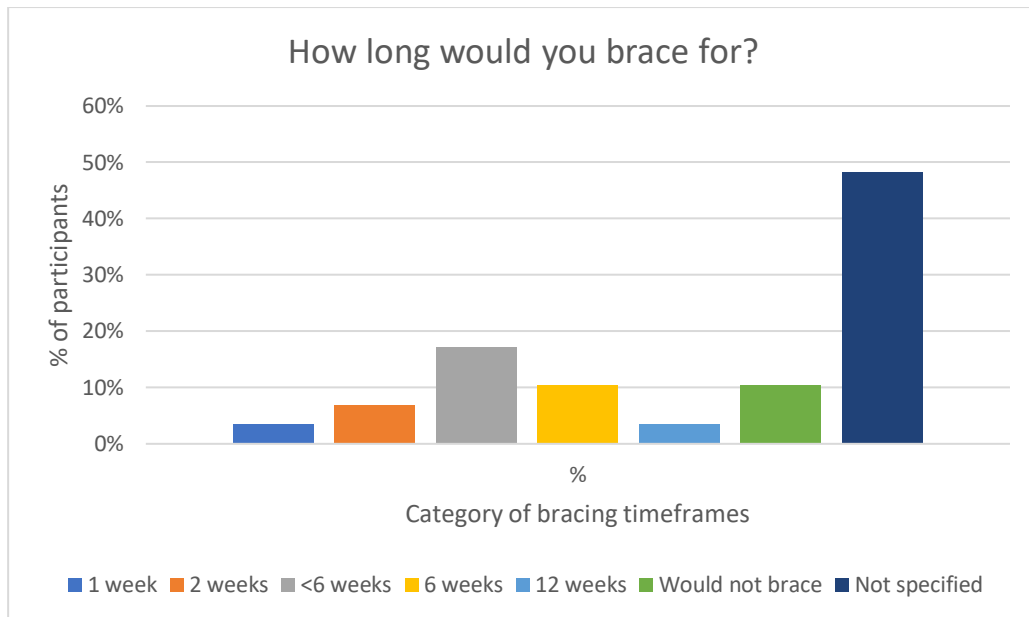


Figure 8: Length of bracing for ACL injuries

3.2.1 Thematic Analysis

A thematic approach was used to assess the open text final question. The following codes were established by highlighting commonalities amongst texts: ‘swelling’, ‘pain management’, ‘movement and weight bearing (WB) restrictions’, ‘bracing and immobilisations’, ‘strength and gait normalisation’, ‘ROM and proprioception work’, ‘imaging or knee clinic referral’, ‘risk of secondary injury’, ‘reassurance and discussion management’, and ‘generic rehabilitation’. The frequency of how many times each ‘code’ was mentioned can be seen in Table 10.

Table 10: Codes for text responses for question ‘What advice would you give a patient that was highly suspicious of an ACL injury?’

CODES	COUNT
SWELLING	13
PAIN MANAGEMENT	5
MOVEMENT AND WB RESTRICTIONS	15
BRACING AND IMMOBILISATIONS	5
STRENGTH AND GAIT NORMALISATION	11
ROM AND PROPRIOCEPTION WORK	10
IMAGING OR KNEE CLINIC REFERRAL	9
RISK OF SECONDARY INJURY	3

REASSURANCE AND DISCUSSION MANAGEMENT

7

GENERIC 'REHABILITATION'

9

These codes were grouped into themes: 'Immediate effusion management', 'offloading and caution', 'sub-acute movement and loading', 'further diagnostics and education' [Figure 9]. These 4 themes were considered as the overarching themes of ACL care which encompassed the 4 stages from initial acute management to onward referrals [Table 11]. The frequency of each theme mentioned amongst the participants are detailed in Table 8. As each of the 4 stages represent a different aspect in patient advice/care, it was documented how many themes each participant mentioned in their answer, as documented in Table 9. Only 10% of participants mentioned all 4 themes of acute management advice, 24% of participants mentioned 3 themes and 1 theme respectively, and 41% of participants mentioned 2 themes [Table 12].

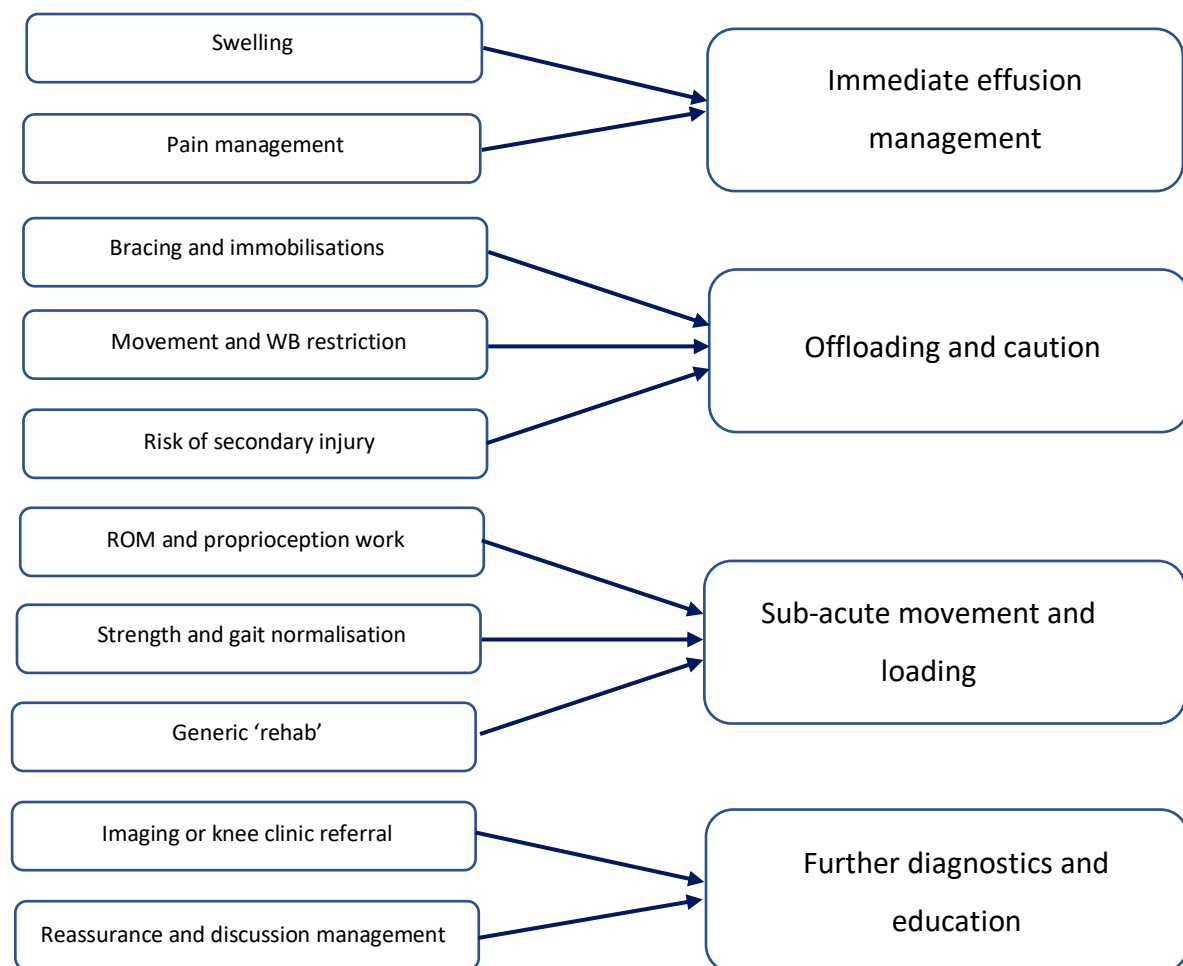


Figure 9: Code to Theme Relationship

Table 11: Theme frequency count

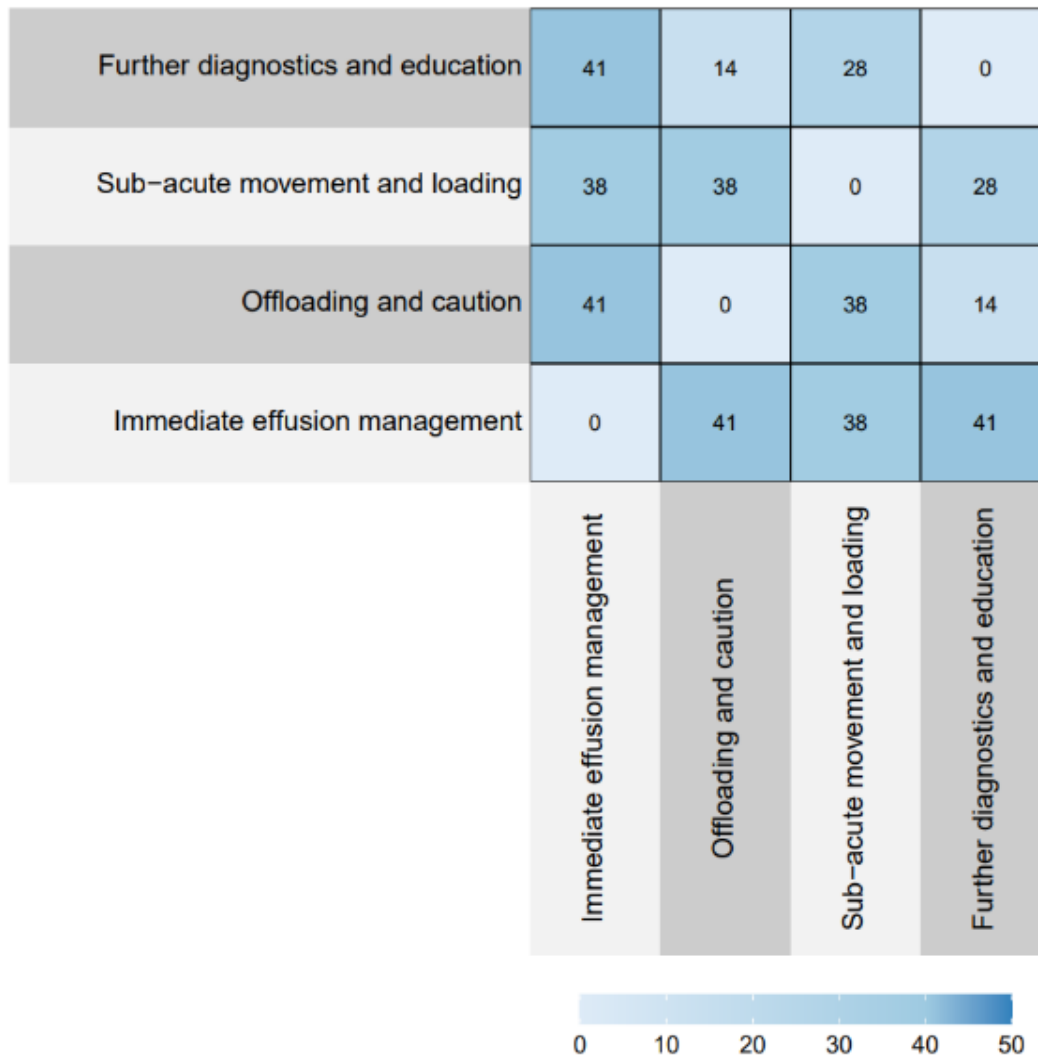
THEMES	FREQUENCY
IMMEDIATE EFFUSION MANAGEMENT	14
OFFLOADING AND CAUTION	17
SUB-ACUTE MOVEMENT AND LOADING	19
FURTHER DIAGNOSTICS AND EDUCATION	14

Table 12: Number of themes each participant included

NUMBER OF INCLUDED THEMES	FREQUENCY
4	10%
3	24%
2	41%
1	24%

The relationship between the frequency of themes mentioned in combination were investigated using a heatmap [Figure 10]. Whilst there was no overwhelming relationship established, it was noted that ‘offloading and caution’ and ‘further diagnostics and education’ were mentioned in combination the least out of all the groupings.

Figure 10: 2 by 2 table showing association between commonly mentioned themes



3.4 Discussion

Clinician assessment priorities, their confidence in their clinical assessment techniques, and the consistencies within the advised management strategies are discussed within this section. This allows for the current clinical pathway to be defined as well as the identification of areas of contention or ambiguity in the clinical pathway that may benefit from improvement in order to optimise patient care.

3.4.1 Assessment Priorities

The ACL is inherent in the structural support of the knee and is the primary restraint for both anterior and rotary displacements (18). When an injury is obtained, symptoms of giving way at the time of injury or in the after events are common (25, 77). Unsurprisingly, the survey revealed the events recalled by the patient immediately after the injury mechanism were ranked as highly important, supporting existing evidence.

A patient's subjective history is an integral part of the assessment process (39), whilst this is helpful in conjunction with clinical assessment to rule on diagnosis (78), the results from the survey revealed similar subjective history priorities to the established LIMP index.

The mechanism of injury itself was reported as the most important indicator of injury occurrence, clear mechanisms consisting of non-direct-contact injury are the most frequent and are attributed to 88% of all ACL injuries (79). Most injuries are a combination of valgus and rotational knee force, whilst other common mechanisms consist of forced hyper-extension (80, 81). In a previous study evaluating medical records, a 'pop' at the time of injury was reported in 73% of injuries (61); this was also noted as an important diagnostic factor in 59% of survey responses from a prior survey (39).

3.4.2 Confidence in Assessment

The 'feel' for joint laxity is renowned to be one of the most important clinical diagnostic factors in assessing for ACL Injury. Since the ACL plays such a pivotal role in joint stability, excessive movements in the knee's biomechanics will cause the assessor to rule in or exclude ligamentous injury and therefore joint integrity assessment plays an essential part in deciding onward referral and management. It is thought that the more senior and specialised the clinician the better the diagnostic accuracy for these joint stability tests, yet as shown in the

survey, even specialists are not confident in their findings due to the high subjectivity associated with these tests.

MRI remains the gold standard in diagnostic practice, not just for morphological confirmation of the ACL itself but also to visualise surrounding structures such as other ligamentous tissue, bony health, cartilaginous structures and the meniscus. In order for MRI's to be ordered promptly in clinical practice, patients have to be assessed, and fit the clinical criteria to enable imaging. Quantitative assessment tools such as new wearable technologies have the potential to provide objective knee laxity outputs that would support the clinical assessment and improve the clinical picture for both specialists and more generic practitioners and may address some of the confidence issues highlighted in this survey. Their use is explored later in this thesis (Chapter 4).

3.4.3 Bracing Consensus

Bracing is a topic of contention in managing ligamentous knee injuries. It is widely accepted that the non-surgical management and treatment for MCL injuries includes a period of immobilisation and bracing. However, there is disagreement in both the type of brace and the associated duration of wear (82-85).

Whilst there seems to be a more defined protocol for the bracing post-operatively for ACL injuries (86), there appears to be contention surrounding the use of bracing for the acute (pre-surgical or non-surgical) management for ACL injuries; there is also disparity on whether these patients should be immobilised at all. There is no current national consensus on how to immobilise acute ACL injuries pre-operatively to facilitate healing and protect the surrounding anatomical structures.

The rationale and clinical benefit for acute ACL bracing and immobilisation is three-fold (87). It can increase and help somatosensory proprioception to aid neuromuscular control and improve joint position, biomechanically correct abnormal and pathological translation, or rotation of the knee when weight-bearing, and finally reduce the subsequent 'giving way' episodes which can induce micro-trauma to the knee.

It is unsurprising that there was so much variability in responses for brace use in this patient cohort, the disparity within the wider literature further supports the need for up-to-date research in the bracing use and duration for acute ACL injuries (82-85).

The ACL diagnostic process can become lengthy, from original A&E attendance, patients can have up to 5 appointments before diagnosis is reached (7). The uncertainty around diagnosis and the ambiguity in whether patients should consider surgical or conservative management can lead to difficult conversations between patients and clinicians and between clinicians.

3.4.4 Post Injury Advice

In order for patients to receive comprehensive advice post ACL-injury, it was considered that the four stages of healing and post-injury management should be discussed. Initially post-injury the main symptoms described by patients are effusion and pain. Reducing knee effusion is a high priority in managing injury hence why the first category of analysis was bracketed as 'immediate effusion management' (88).

In addition to this, patients can find periods of bracing and immobilisations helpful to aid healing and reduce symptoms of pain and instability. The aim of bracing is to restore knee joint kinematics and surrounding structure strain (87, 89). On the contrary other patients can be premature in their return to certain activities (90), for this reason the 2nd theme encompassed both concepts and was labelled 'offloading and caution'.

After this period the main objectives are for patients to improve range of movement and begin to strengthen surrounding contractile structures. Regaining ROM early post-ACL injury reduces pain, decreases joint haemarthrosis and scar tissue formation, and helps maintain joint viability and articular cartilage health (82), regaining strength to surrounding contractile structures decreases the strain of ligamentous structures and improves knee stability and biomechanics (91). The 3rd theme of 'sub-acute movement and loading' encompasses these principles. Finally radiological verification is sought before appropriate management route is decided and onward relative specialist referral is made, this part of the conversation includes reassurance and advice for the patient once the acute symptoms have resolved. The final theme of 'final diagnostics and education' was thought to encompass this stage.

Whilst ACL management needs to remain patient centred and will deviate depending on the individual patient needs, there needs to be better continuity in how these patients are treated post-acute ACL injury. A bracing protocol that aims to facilitate healing and improve patient symptoms which has clinician discretion to be manipulated for individual patient needs, as

well as a comprehensive advice checklist, would provide the foundation for uniform comprehensive care to be provided.

3.4.5 Limitations

Limitations of this survey must be considered. Firstly, it must be recognised that the response rate was limited to only 30 participants, despite extensive advertisement response was lower than expected. The survey should generate a larger population size to increase generalisability. The population of participants consisted only of specialists that mainly work in out-patient specialist clinics, who are not usually the first practitioner to be assessing this patient group. This should be repeated on a wider population representative of those who assess initially at A&E. Another limitation would be that question 12 and 13 were asked as 1 question despite there being 3 parts to it, the answer was given in a free text format meaning the participant could give only part-answer to the question, this meant parts of the question remained unanswered for some participants, in retrospect it may have been a better choice to ask the questions individually in their respective parts.

3.5 Summary

Acute knee assessment is based on clinical judgement that is highly dependent on the assessment of knee stability. Ligamentous injuries that lead to instability, particularly the ACL, often lead to lifelong complications and degenerative changes, as well as pain and debilitation in the more acute stages. The current methods to identify an ACL tear rely on an experienced clinician to objectively assess the knee and synthesise their findings with confidence, the current pressures on the healthcare system make it almost impossible for patients to access such specialist opinions at urgent care centres such as A&E. Measurable outputs of joint laxity will help improve diagnostic accuracy and speed, should improve efficient decisions about MRIs and onward surgical referrals, thus leading to better and faster patient outcomes.

Defined care pathways for this patient group will ensure patient receive specialist advice as early as possible and reduce unnecessary appointments. Ambiguity regarding which service to refer to only prolong patient care and increase hospital expenses. However, the establishment of such pathways is beyond the scope of this thesis.

There seems to be no consensus amongst specialist clinicians on the bracing of acutely injured ACL, there is much disparity on whether bracing is appropriate, the type of brace and the

duration of immobilising these patients. A specified bracing consensus for ACL injuries is required. This may require further studies investigating the effect of bracing immobilisations on the ability for the ACL to self-heal. Bracing may also help to reduce patient symptoms, protect surrounding knee structures but again further research is required.

It appears that there are inconsistencies within the acute and longer-term management advice for these patients. ACL recovery is a long and complicated recovery, better education for both specialised and non-specialised clinicians on management advice for patients will ensure patients are more enlightened in their diagnosis and their care path which encourages shared decision making- an integral component of NHS NICE guidelines (92).

4 The Biomechanics of Knee Laxity

4.1. Introduction

Laxity is the objectively measured parameter which is symptomatically described as the feeling of instability (93), it is a predetermining factor in long-term knee joint health and individual function (4, 94, 95). Unlike the hip joint, the knee is inherently more unstable due to its structural anatomy, as it has a much smaller congruency of articulating surfaces. Consequently knee stability relies more heavily on the ligamentous structures (17).

This chapter outlines the biomechanical breakdown of knee laxity and sets out the current methods available used to quantify it. It does this by including a detailed breakdown of how laxity manifests in the ACL injured knee and the importance of considering multiplanar complex analysis. This chapter also includes a scoping review which has been submitted for publication and is under review.

4.2. Anterior Posterior (AP) Laxity

AP laxity has been extensively investigated (89, 96-101), with anterior translation of the tibia on the femur historically assessed through clinical tests such as the anterior draw, Lachman and pivot shift tests (67). A positive test being the subjective “feel” of excessive anterior laxity, usually compared with the healthy uninjured limb.

The ACL acts as the primary restraint to AP translation; resisting approximately 85% of the movement (102). The amount of AP translation is dependent on the degree of flexion in the knee joint due to the change in joint congruency at differing angles of knee flexion (103). The amount of tibial anterior displacement induced can be affected by multiple factors. For example, the degree of internal or external torque applied to the knee can change the tightness of the peripheral knee structures and can subsequently alter the amount of tibial anterior displacement (102-104).

Although not currently used in clinical practice, devices like the KT1000 were devised to quantify AP translation in a clinical environment and historically a 3mm of side-to-side anterior translation was deemed pathological and indicative of an ACL Injury (105). Such devices however have decreased in popularity due to concerns regarding reliability and the inability to assess components of rotational laxity (106).

4.3. Rotational Laxity

The lack of joint congruency in the knee permits rotational laxity, which is primarily restrained by the extra-articular ligaments, the ACL is also responsible for maintaining tibial rotational stability (18). Increased availability of technological capability to accurately measure 3D motion has increased research work into quantifying the effect of rotational laxity (18).

When the ACL is intact it becomes taught during knee movement to ensure that the natural axis of rotation is around the centre of the tibial plateau. In an ACL deficient knee there is no tension and thus knee stability relies on the PCL and the extra-articular collateral ligaments to control knee movement. The axis of rotation is therefore thought to shift medially (102).

The anatomical structure of the knee means that the lateral joint capsule has more movement than the medial, a feature also controlled by the capsular attachments of the menisci (102). Due to the natural concave shape of the medial tibial plateau, when loaded the medial femoral condyle is stabilised in the respective tibial articulating surface which acts as a pivot point that the lateral compartment can move around (102). Like AP displacement, rotational laxity increases in the flexed knee (107).

There has been variation in how rotational laxity is calculated, generally the flexion-extension angle and axis of rotation must be established (18), (102, 107-109). Historically, rotational laxity has been measured via various wearable systems on cadaveric knees using the axis of rotation as the centre of the tibial plateau and the subsequent rotational angular change measured. This methodology is based on the assumption that the axis of rotation is within the midpoint of the knee, whilst this may be true of the intact ACL knee, it is not when ligamentous integrity is compromised (102).

In an ACL injured knee, the axis of rotation shifts medially, thus magnifying the movement of the lateral compartment in comparison to the medial. When associated collateral concomitant injuries at the knee occur this impacts the position of the axis of rotation (102). When the LCL and lateral complex is damaged in addition to the ACL this further destabilises the lateral knee compartment by decreasing its structural integrity causing a further increased laxity in the lateral compartment thereby increasing tibial internal rotation, which due to the natural coupling of movement gives rise to anterior lateral rotary laxity (102, 110). When the

medial compartment is damaged the axis of rotation changes by moving laterally causing an increase in anteromedial rotary laxity.

In addition, using the angular change of the axial plane as a measure of rotational laxity assumes the flexion-extension angle of the knee remains the same throughout the test performance, changes in the sagittal plane would subsequently effect those in the axial plane due to coupled movement that naturally occurs in the knee (107-109).

Research interest around rotational laxity has grown in recent years following the knowledge that excessive rotational laxity is one of the main reasons for ACL graft failure (18), specifically persistent medial joint laxity increases ACL strain which leads to a higher chance of graft rupture (111, 112).

4.3.1. Antero-Medial Rotatory Laxity (AMRL)

AMRL is a particular sub type of rotational laxity, historically this has been an overlooked feature of ACL injuries. AMRL is excessive valgus strain, anterior translation and associated tibiofemoral external rotation. In vivo, it is difficult to quantify and there are very few clinical tests capable of isolating such a nuanced movement, the Slocum and Larsen test was the first to do so in 1968, however the lack of equipment available at that time meant this test was never quantified (113).

The late John Feagin Jr, discussed the importance of AMRL and devised a simple clinical examination for the problem, now known as the Feagin Thomas test. This test is explained in detail in 5.2.14, in essence it involves testing the integrity of the deep MCL fibres which is hypothesised to be the primary restraint of AMRL (114).

MCL tears are seen to increase ACL strain, where strain is considered a change in length from its original state (115). ACL reconstructive surgeries are often delayed to allow for MCL healing (21), Mancini concluded that the restoration of MCL biomechanics is integral for subsequent ACL protection and ACL graft protection, especially during explosive dynamic activities (21). Using a hamstring autograft for ACL reconstruction may potentially exacerbate AMRL due to the change in knee dynamics post-surgery (102). The hamstring muscles play a crucial role in stabilizing the knee against rotational forces. When these tendons are harvested for grafting, the loss of muscle can weaken the knee's resistance to internal rotation, potentially increasing the risk of medial and rotational instability. The alteration in the knee's biomechanical

behaviour post-surgery could therefore contribute to or worsen AMRL, underscoring the importance of a comprehensive evaluation and rehabilitation to address these potential issues.

4.4. Static Vs Dynamic Laxity

Clinically laxity assessments are underpinned by the clinician's 'feel' of how much excessive movement the assessor can induce. This is not only subjective and dependent on the examiner's experience but is also restricted to static positions. Static laxity refers to the looseness or instability of the knee joint when it is not under any dynamic load or movement. This is typically assessed when the joint is at rest and is not necessarily reflective of the laxity envelope of the knee under different conditions (116, 117). Dynamic laxity, on the other hand, refers to the instability or looseness of the knee joint during movement or under functional loading conditions (116, 117).

When joint laxity is assessed, it should be considered under 3 different scenarios: the maximal amount of laxity in a single plane induced under a controlled load; the coupled joint laxity, this is the total laxity across multiple planes (i.e. rotation and anterior translation); and the laxity that is induced from a loaded mechanism, this is dynamic laxity when walking or subluxation of the knee caused from a 'giving way' mechanism (18).

Studies have begun to explore features of this using IMU sensors during a pivot shift test, the pivot shift test induces a similar giving way mechanism to that experienced by patients when walking (18). This clinical test produces large spikes in acceleration and deceleration data from the IMU which shows promise for extracting features of laxity from wearable sensors.

Arthrometers have the ability to assess AP laxity in a static position only, i.e., when the knee is in a degree of flexion and an external force by the assessor is induced. Wearables and motion capture, however, have the potential to measure metrics of laxity in more than one plane, during loaded dynamic conditions. An extensive review of all current methods and approaches to assess laxity can be found in 4.6.

4.5. Screw Home Mechanism

During gait, the ACL plays an essential role in 'locking' and 'unlocking' the knee (20). There are anatomical discrepancies between the medial and lateral condyle surfaces of the tibial plateau (20, 102), the medial tibial condyle is concave whilst the lateral is convex. In addition,

the medial femoral condyle is also naturally longer, this means that the lateral tibiofemoral joint is incongruent (20). In order to assure total knee congruency, the knee undergoes coupled rotation in addition to flexion and extension as it moves through its range of motion. This coupled movement occurs in the in the last 20 degrees of extension; this is known as the screw-home mechanism (20).

The ACL tightens during terminal extension during the screw-home mechanism, when the collateral ligaments tighten in extension, external rotation of the knee occurs as a consequence of a prolonged anterior glide of the medial side of the knee and further tightening of the lateral condyle (20). This helps stabilise the knee during extension (19, 20) and prevents subluxation and anterior translation during deep flexion (17, 19). The reverse happens when the knee unlocks and begins to flex, the ACL pulls the tibia to glide posteriorly causing internal tibial rotation, and this process is initiated by contraction of the popliteus decreasing tension on the collateral ligaments.

When the integrity of the ACL has been compromised, patients often complain of the knee 'giving way'. This is a result of the reduced stability and stiffness in terminal extension that the ACL would normally provide and the subsequent loss of the screw home mechanism (100). It is thought that this 'giving way' is due to this deficit in rotational stability. Likewise the pivot shift avoidance gait is the adaptive strategy during the gait cycle to avoid rotational laxity and subsequent 'giving way' of the knee joint (118).

When loaded, the ACL is responsible for tightening the knee to prevent tibiofemoral anterior translation and internal rotation (118, 119). When the ACL is deficient, the quadriceps complex draws the lateral tibial plateau anteriorly and the femur rolls posteriorly whilst the lateral femoral condyle "falls off" the tibial plateau giving rise to anterior lateral rotary instability (118, 120). When performed at speed and loaded the joint is in essence subluxing; which is perceived by the ACL deficient person as a 'giving way' of the knee (118). The ACL deficient person, therefore, produces compensatory adaptation strategies to avoid this subluxation occurring known as the pivot shift avoidance gait (118). Generally, this includes a higher knee flexion angle and reduced internal rotation knee moment during the weight bearing stages of the gait cycle (118, 121).

4.6. The Methods of Quantifying Knee Laxity in the ACL injured Population: A Scoping Review

4.6.1.1. Declarations

The contents of this section have been submitted for publication and are under review.

4.6.1.2. Introduction and Aims

This review seeks to scope the current methods employed to quantify knee laxity in the ACL injured population group. There has been much development in technological advancement in recent years which has provided new ways to measure joint laxity, this scoping review provides a systematic approach to evaluate the methods historically and presently used to measure knee laxity during clinical assessment.

4.6.2. Background

ACL injuries occur frequently with an annual incidence of 30 cases per 100 000 people within the UK, and up to 50 000 reconstructive surgical operations performed annually (122, 123). An estimated £63-85 million was spent on ACL reconstructions alone in 2015, not accounting for the cost of rehabilitation, appointments, and associated investigations required for the diagnosis and management of this debilitating injury (124).

In addition to prematurely ending sporting careers and participation, ACL injuries can severely impact the ability to work and even in some cases, it can be associated with symptoms of anxiety and depression (125). Fast, accurate diagnosis and subsequent management is essential for enhancing patient outcomes and reducing pressures on NHS services. ACLs are responsible for maintaining anterior and rotary knee stability, ruptures to the ACL therefore give rise to increased joint laxity in both of these planes (106, 126). The laxity tests performed can be graded as per the amount of laxity the examiner feels (127), and reports of sensitivity and diagnostic accuracy vary between studies in part attributable to the skill and experience of the examiner perform and interpret test findings and ultimately successfully diagnose ACL tears (128).

Consequently, quantifiable methods to determine knee instability within clinical settings have been sought to help efficiently diagnose and manage this condition. Technological advancements over the years have now made it possible to quantify knee laxity using motion

capture tools and other approaches, including wearable devices. Different approaches to assessing laxity are outlined below.

Early arthrometry devices, like the KT-1000 arthrometer, have been used to measure anterior tibial translation (ATT) relative to the femur (36). An arthrometer is an instrument that is secured over the anterior surface of the tibia; it involves a casing with two sensor pads positioned over the patella and tibial tubercle with the leg typically fixed at an angle of 30 degrees. A variable force is applied to induce ATT in the leg as a means of determining instability. However, the reliability of the KT-1000 between raters to measure knee laxity has been called into question, limiting its clinical applicability (37).

The emergence of wearable technology has enabled the incorporation of technology such as inertial measurement units (IMUs) which offer new approaches to the assessment of instability namely acceleration and angular velocity. A commonly used commercial system utilising IMUs is KiRA (Orthokey LLC, Lewes, DE, USA); this device is mounted onto the skin over the lateral aspect of the anterior tuberosity of the tibia via a strap to measure acceleration during tests such as the pivot shift or Lachman's (129).

Electromagnetic measurement systems (EMS) have also been used to capture joint laxity by calculating joint motion through displacements within an electromagnetic field generated by a transmitter and associated receiver. These system can measure tibial acceleration (as ms^{-2}) or translation (mm) (130). However, the set-up is costly, subject to errors and has to date remained a research tool although it has been suggested as a means to improve clinical diagnosis (131).

Optical motion capture system are frequently used to capture knee joint laxity and are often used to measure changes in gait following ACL injury (118). They have also been used to validate synthetic models of ACL-compromised knees (132). However, the use of optical motion capture in clinical practice proves challenging due to logistical elements such as cost, timely set-up, and equipment needs (133). There are also errors that can arise from incorrect marker placement and skin artefacts during movement (134). Although 'marker less' motion tracking devices are emerging as an alternative, they currently lack precision for capturing joint laxity (135).

Dynamic MRI approaches have also evolved to capture joint laxity. Patients are placed in an open MRI scanner which gives access for the examiner to manipulate the leg during testing (136). Although useful and capable of robust quantitative metrics, their clinical utility is limited due to high costs and specialist interpretation requirements and limited availability of open MRI scanners (137).

In summary, while numerous technologies have the capability to measure and quantify knee laxity, few are readily available or practical for routine clinical use. As the focus in ACL diagnosis shifts increasingly towards objective measurement, this scoping review aims to evaluate and summarise the various methods used to assess knee instability following ACL injury. It will examine the outputs and metrics of reliability and accuracy associated with these methods, with the goal of identifying gaps in the literature and determining which technologies hold the most promise for translation into clinical practice.

4.6.3. Materials and Methods

4.6.3.1. Search Strategy

The literature search was conducted via a systematic approach using the databases: MEDLINE, EMBASE and CINAHL, and Scopus. Published articles up until the 24th of October 2022 were eligible for inclusion. The Boolean search strategy was used to combine terms of interest and retrieve all relevant articles within this area (Appendix C: Search Strategy for Scoping Review) 'Knee instability', 'method of assessment', and 'clinical test' were the topic groups of interest that encompassed the associated keywords and subject headings used to complete the search. All keywords and subject headings within the respective topic heading were combined with 'OR', topic groups were then combined with 'AND'. A hand search was also undertaken which cross referenced the terms of Appendix C against the bibliographies of relevant articles.

4.6.3.2. Eligibility Criteria

This review scoped the current approaches to quantifying knee instability in ACL injured participants. For studies to be considered as eligible for the review, they had to meet the following eligibility/inclusion criteria: (1) participants had a confirmed full or partial ACL injury (2) ≥ 1 quantifiable assessment tool stated in the protocol, and (3) a study output classified as a 'direct clinical' measure of knee instability.

As shown in [Figure 11], the exclusion criteria applied to studies for screening were; incorrect outcomes, incorrect study design, incorrect publication year, previous ACL injury or comorbid knee pathology (e.g. osteoarthritis), the knees were examined under anaesthesia, animal/cadaveric knees were used, study not available in English (without option for translation), or unable to obtain access to full text available via the library.

Inappropriate study designs that were excluded from this review were: case series, case studies, scoping reviews, and systematic reviews. Only studies published on or after the year 2000 were considered in this review. This timeframe allows for the consideration of advancements in medical techniques and technologies that older studies might not reflect. Additionally, it helps to avoid outdated practices and ensures that the review's conclusions are based on current standards of care and knowledge.

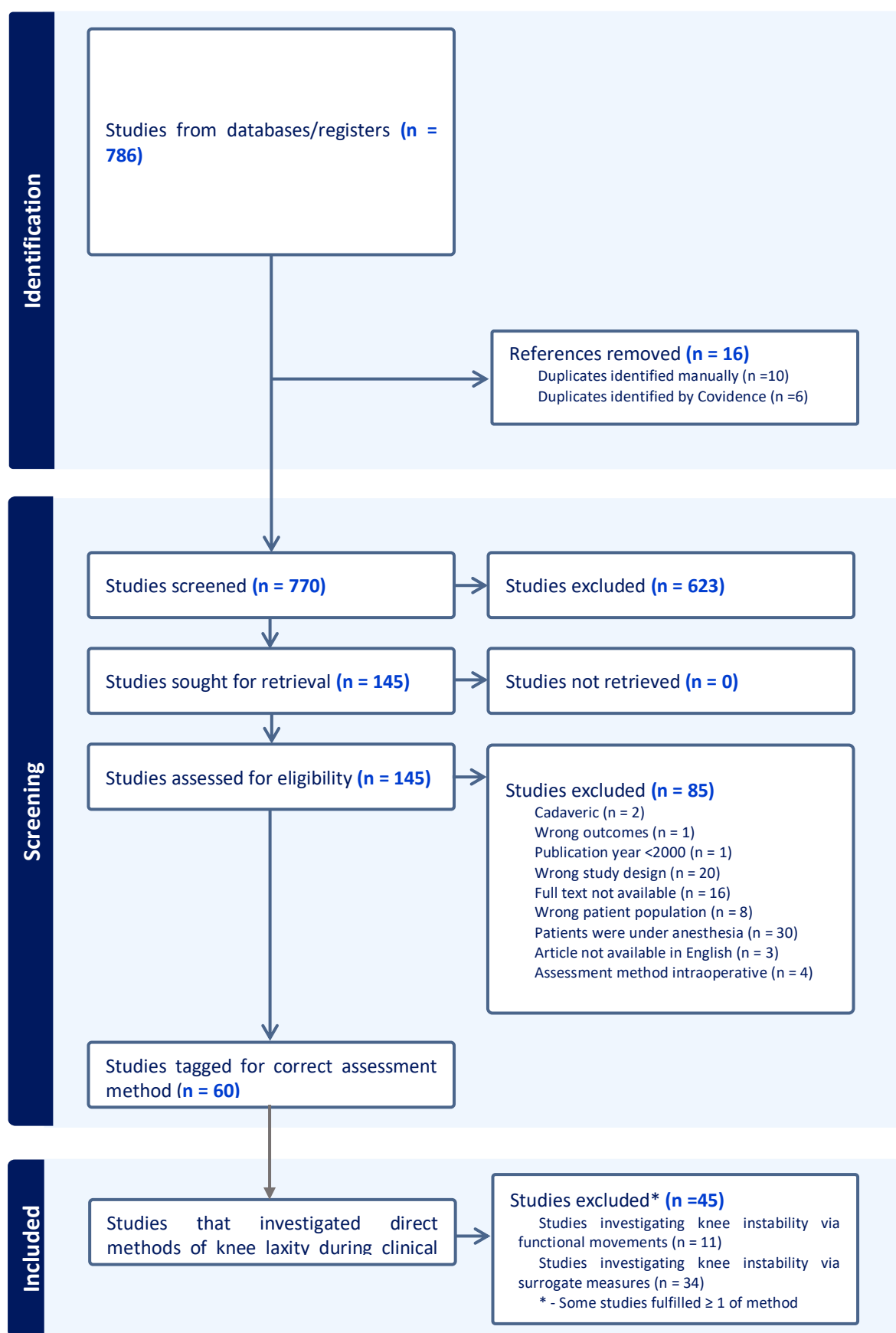


Figure 11: PRISMA diagram

4.6.3.3. Selection Process

The retrieved studies that were filtered through the search strategy (Appendix C: Search Strategy for Scoping Review) were exported to the reference management software EndNote X20 (Clarivate Analytics, Philadelphia, PA, USA), and duplicates removed. The remaining studies were exported to the reference management platform Covidence (Veritas Health Innovation, Melbourne, Australia) to undergo title-and-abstract screening, and subsequently, a full-text review. The studies were further screened against the inclusion-exclusion criteria by three independent reviewers (PhD candidate and 2 medical students working under the author's supervision); any discrepancies that arose were resolved through discussion with the PhD candidates' supervisors. Our initial search of the literature revealed 786 studies, 16 duplicates were found and removed. A total of 770 study titles and abstract were screened, and a further 623 studies excluded (Figure 11). The 147 studies remaining underwent a full-text review, and another 85 studies were excluded. Of the 60 studies remaining, 19 studies were identified as quantifying dynamic knee instability through a direct and clinically applicable measure and deemed suitable for inclusion.

4.6.3.4. Data Extraction

The following demographic data were extracted from each study and recorded in Table 13: author; year of publication; total participant number (along with any notable methods of stratifying patients); additional injuries to the joint (e.g. any lesions to the meniscus or cartilage); participant age; participant gender ratio (presented as an unsimplified ratio); the type of ACL rupture occurred; the number of healthy knees used in the study; and the time-to-reach-clinical assessment.

4.6.4. Results

4.6.4.1. Patient Demographics

Table 13 shows the patient characteristics and demographic data in each of the studies included in this review. The gender characteristics were presented as a ratio of male-to-female-non-specified, where gender was not explicitly stated. The time taken from injury to clinical assessment was presented either in months or in days.

Table 13: Participant Demographics of included studies

Author (Year)	Total participa nts with ACL injury (n=% full ACL ruptures)	Other Injuries					Unaffected Knees		Mean Time from Injury to Assessme nt (Standar d deviation Range)	Mean Age (SD Range) (years)	Gender (unsimplifi ed M:F:NS)
		Medial meniscu s	Lateral meniscu s	Both menis ci	Unspecifi ed meniscus	Cartila ge	Contralate ral	Healthy participa nts			
Berruto et al. (2013)(138)	100 (100%)	35	9	2		-	100	-	-	29 (9) 16-45	65:35:0
Caracciolo et al. (2021)(139)	70 (100%)	-	-	-		-	70	-	-	30.8 (10.4) 20-50	62:8:0
Fok et al. (2014)(140)	225(81%)	75	109	-		-	225	-	-	26.4 [‡] (7.6) 16-52	189:36:0
Kim et al. (2021)(141)	67 (100%)	27	24	-		1	67	-	-	31.3 [‡] (8.7) 20-50	55:12:0
Labbe et al. (2010)(142)	70 (N/S)	-	-	-		-	57	-	-	-	-
Labbe et al. (2015)(143)	13 (N/S)	-	-	-	5	-	13	-	-	15.5 (1.5)	8:3:2
Logan et al. (2004)(136)	10 (N/S)	-	-	-		-	10	-	30 months 5-120	35 21-64	7:3:0
Lopomo et al. (2017)(144)	103 (85.4%)	38	40	-		-	102	-	-	27.0 (9.3) 15.6- 48.0	60:42:1
Matsushita et al. (2013)(145)	50 (88%)	-	-	-	24	-	50	-	11.5 months 18-33	26.6	28:22:0
Mayr et al. (2021)(146)	24 primary ACL ruptures	6	11	-		Medial (7)	24	-	58.8 days (34.0)	31.3 (9.1)	14:10:0
						Lateral (4)					
						Patella femora l (6)					
	23 (re- ruptures)	11	7	-		Medial (13)	23	-	50.8 days (47.5)		27:20:0

						Lateral (7)				31.2 days (6.7)	
						Patella Femor al (8)					
Muccioli et al. (2018)(147)	60 (100%)	20	10	3		-	60	-	-	34 (± 15.4) 14-51	42:18
Senorski et al. (2018)(148) ***	86 (87.2%)			53 NS		13	86		1 year group 128 days (86) 2-year group 139 days (84)	1 year group 24.80 (9.25) 2-year group 23.88 (9.24)	49:37:0
Nishida et al. (2020)(149)	94 (N/S)	25	20	3		-	94	-	9.6 months (3.8)	27.3 (±11.8)	44:50:0
Osti et al. (2011){Osti, 2011 #70}	Over 50	20 (100 %)	8	3	-	10	20	-		50-62	12:8:0
	Under 30	20 (100 %)	3	3	-	2	5	20	-	17-30	12:8:0
Patel et al. (2003)(150)	44 (100%)	-	-	-	-	-	-	44	21 (± 31) 1-124 months	29 (±9) (ACL) 30 (±9) (Health y)	25:19:0
Raggi et al. (2019)(15)	20 (100%)	-	-	-	-	-	20	-	-	25 (10) 16-51	17:3:0
Sundemo et al. (2018)(151)	103 (86.4%)	38	38	-	-	-	103	-	-	24.6 (9.1) 14-50	56:40:0
Svantesson (2018)(96)	58 (N/S)	16	14	9	-	-	58	-	-	27.1 (9.8)	34:24:0
Wiertsema (2008)(37)	20 (100%)	-	-	-	-	-	20	-	-	30 (8.1) 17-44	14:6:0

Participant Demographics, showing all of the demographic data recorded from the studies included for this scoping review. In studies where demographic data such as participant mean age was stratified according to participant groups (‡), a combined mean and standard deviation was recorded for each study and recorded. NS = not specified

4.6.4.2. Quantification of Knee Laxity

Table 14 depicts values of quantitative dynamic knee laxity measurements, each classified to the device used in the study. In the event where there were multiple methods to measure dynamic knee laxity, for example Senorski et al. 2018 (96), data was recorded and classified to each device respectively.

For each study quantifying knee instability data on the participant population, methods of quantification, use of diagnostic verification and any metrics of sensitivity, accuracy or specificity were extracted. Any paper that included multiple values of knee laxity for further differentiated patient populations that fit the inclusion requirements of this study were combined and a meta mean calculated. Due to the heterogeneity of how sensitivity was recorded, direct quotations of any related measure of sensitivity were recorded in Table 14.

Table 14: Results Table Detailing the Device used to Measure Laxity, the corresponding result of laxity along with its associated sensitivity and the means of verifying the ACL diagnosis.

Author	Clinical test	Device	Arthrometer		
			Result	Sensitivity	Verification
Fok et al. (2014)[†] (140)	Lachman's	KT-1000	Side-to-side difference in ATT (mm), Mean $\pm$ SD. lbs 15 = 1.9 +1.70 20 = 3.0 +2.31 30 = 4.1+ 2.91	Not stated	Arthroscopy
Kim et al. (2021)[†] (141)	Lachman's	KT-2000	Side-to-side difference in ATT (mm), Mean $\pm$ SD = 30lbs= 4.7 $\pm$ 2.05	Not stated	MRI and Arthroscopy
Matsushita et al. (2013)[†] (145)	Lachman's	KT-1000	Absolute value ACL-deficient in ATT (mm), Mean $\pm$ SD = 14.8 $\pm$ 3.7 Side-to-side difference in ATT (mm), Mean $\pm$ SD (mm) = 5.6 $\pm$ 2.6	Not stated	MRI and Arthroscopy
Mayr et al. (2021)[†] (146)	Lachman's	Laxitester	Side-to-side difference Internal Rotation Angles, Mean $\pm$ SD = 3.6 $\pm$ 4.5° Side-to-side diff. External Rotation Angles, Mean = 3.4 $\pm$ 3.3°	Accuracy report as 5°.	Arthroscopy

		KT-1000	Side-to-side difference in ATT (mm), = 4.0 ± 1.7 mm	Not stated	
Nishida et al. (2020)[†] (149)	Lachman's	KT-1000	Side-to-side difference in ATT (mm), Time after injury (months) <3 = 6.1 ± 3.3 3-6 = 6.1 ± 2.7 6-12 = 5.4 ± 2.9 >12 = 5.7 ± 3.2	Intraclass coefficient (ICC) values of 0.47 to 0.95.	Arthroscopy
Osti et al. (2011)[†] (152)	Lachman's	KT-1000	Side-to-side difference in ATT (mm), Over-50 group (n) <3mm = 0 3-5mm = 5 >5mm = 15 Over-30 group (n) <3mm = 0 3-5mm = 7 >5mm = 13	Not stated	MRI and Arthroscopy
Patel et al. (2003)[†] (150)	Lachman's	KT2000	Side-to-side difference in ATT (mm), Mean $\pm$ SD = 6.5 ± 3.0 mm	Not stated	Arthroscopy and Clinical Orthopaedic Evaluation
Raggi et al. (2019)[†] (15)	Lachman's	KT-1000	Absolute value ACL-deficient ATT (mm), Mean $\pm$ SD = 13 ± 3 Side-to-side difference ATT (mm), Mean $\pm$ SD = 4 ± 2	Sensitivity (0.93), specificity (0.93), accuracy (0.93) and positive predictive value (6.9) for diagnosing an ACL rupture. References van Eck et al. 2013)(69) Intra-examiner repeatability, ICCEx1 = 0.89 for the Examiner 1,	MRI

				ICCEx2 = 0.88 for the Examiner 2. Inter-operator repeatability resulted ICC Ex1-2 = 0.79	
Senorski et al. (2018)[†] (148)	Lachman's	KT-1000	ATT (mm), Mean $\pm$ SD. 30lbs Absolute value for ACL- injured leg = 10.2 ± 3.1 Side-to-side difference = 3.7 ± 2.7 Manual maximal force ACL-injured = 10.9 ± 3.6 Side-to-side difference = 4.2 ± 2.8 Lachman's dichotomous translation 1-5mm translation = 40.2% 6mm+ translation = 59.8%	Not stated	Arthroscopy
Svantens son (2018)[†] (96)	Lachman's	KT-1000	ATT (mm), Mean $\pm$ SD. 30lbs ACL-injured leg = 10.03 ± 3.1 Healthy leg = 6.24 ± 1.84 Side-to-side difference = $3.79 \pm 3.22^*$ Manual maximal force ACL-injured leg = 11.28 ± 3.64 Healthy leg = 6.90 ± 2.05 Side-to-side difference = $4.38 \pm 3.70^*$	Not stated	Arthroscopy
		Rolimeter	ATT (mm), Mean $\pm$ SD. ACL-injured leg = 9.17 ± 2.41 Healthy leg = 4.67 ± 1.78 Side-to-side difference = $4.5 \pm 3.09^*$		

Wiertsema (2008)[†] (37)	Lachman's	KT-1000	ATT (mm), Mean $\pm$ SD. Affected leg = 11.5 ± 2.63 mm Healthy leg = 7.53 ± 2.90 mm Side-to-side difference = 3.96 ± 3.49 mm*	The ICCs for the KT1000 arthrometer were 0.47 (p=0.02; 95% CI=0.03–0.75) for intra-rater reliability and 0.14 (p=0.27; 95% CI=-0.32–0.55) for interrater reliability.	MRI or Arthroscopy
IMU					
Berruto et al. (2013)(138)	Pivot Shift	KiRA	Tibial acceleration (ms ⁻²) Side-to-side difference ACL-injured leg $a_{\max} = 0.4 \pm 0.1$ $a_{\min} = 0.5 \pm 0.2$	Not stated	Arthroscopy
Caracciolo et al. (2021)(139)	Pivot Shift	Triaxial accelerometer	Tibial acceleration (ms ⁻²) Range ($a_{\max} - a_{\min}$) ACL-injured leg = 2.73 ± 1.19 non-injured leg = 3.07 ± 1.20	Not stated	MRI and Arthroscopy
Labbe et al. (2015)(143)	Pivot Shift	IMU Inertial Sensor Unit	Tibial acceleration (ms ⁻²) Pivot Shift Grade Grade 0 = 1.3 ± 3.2 Grade 1 = 2.9 ± 3.2 Grade 2 = 5.2 ± 3.0 Grade 3 = 11.7 ± 7.3 Femoral acceleration (ms ⁻²) Pivot Shift Grade Grade 0 = 0.6 ± 1.6 Grade 1 = 1.4 ± 1.3 Grade 2 = 7.0 ± 3.4 Grade 3 = 7.8 ± 2.2	The stated accuracy of the devices is ± 0.03 g in linear acceleration and ± 1 in angular velocity	MRI
Lopomo et al. (2017)(144)	Pivot shift	KiRA	ACL-injured leg Tibial acceleration (ms ⁻²) = 3.7 ± 1.5 Side-to-side difference Tibial acceleration (ms ⁻²)	Reports an error in value of correlation with underlying	Arthroscopy

			$= 0.8 \pm 1.3$ ACL-injured leg Lateral compartment translation (mm) $= 2.2 \pm 1.7$ Side-to-side difference Lateral compartment translation (mm) $= 1.2 \pm 1.6$	bone movements of less than 8% in clinical settings.	
Mucciolo et al. (2018)(14 7)	Pivot shift	KiRA	Tibial acceleration (ms^{-2}) Side-to-side diff. Range ($a_{\max} - a_{\min}$) $= 2.0 \pm 1.0 \text{ m/s}^2$ according to IKDC Grading (all in m/s^2) IKDC-A = 0.30 ± 0.3 IKDC-B = 0.8 ± 0.3 IKDC-C = 1.7 ± 0.8 IKDC-D = 2.9 ± 0.9	Not stated	Arthroscopy
Raggi et al. (2019) (15)	Lachman's	KiRA	Tibial translation, Mean ACL injured = 9 ± 3 mm Tibial Translation, Side-to-side difference $= 4 \pm 2 \text{ mm}$	Not stated	MRI
Senorski et al. (2018)(14 8)	Pivot Shift	KiRA	Tibial Acceleration (ms^{-2}), Mean $\pm$ SD. ACL Injured leg = $3.46 \pm$ 1.75 Side-to-side difference = 1.00 ± 1.48	Not stated	Arthroscopy
Sundemo et al. (2018)(15 1)	Pivot Shift	KiRA	Tibial Acceleration (ms^{-2}), Median Beighton Score of Joint Hypermobility 0-4 ACL-injured leg = 3.50 Healthy leg = 2.70 Side-to-side difference = 0.60 5-9 ACL-injured = 3.50	Reports an intra-class correlation coefficient of 0.79.	Arthroscopy

			Healthy leg = 2.60 Side-to-side difference = 0.60		
Svantesson (2018)(96)	Pivot Shift	KiRA	Tibial Acceleration (ms^{-2}) ACL injured leg. = 3.71 ± 1.66 Tibial Acceleration Healthy leg (ms^{-2}) = 2.88 ± 1.11	Intraobserver and interobserver intraclass correlation coefficient reported as 0.90(153)	Arthroscopy
EMS					
Labbe et al. (2010)(142)	Pivot Shift	Electromagnetic Motion Capture Sensors:	Total translation magnitude (mm) Pivot Shift Grade Grade 0 = 14.4(6.9) Grade 1 = 15.8(6.4) Grade 2 = 15.8(6.9) Grade 3 = 16.9(5.4) ML translation magnitude (mm) Pivot Shift Grade Grade 0 = 2.2(12.6) Grade 1 = 2.6(11.7) Grade 2 = 3.2(11.4) Grade 3 = 3.3(13.3) AP translation magnitude (mm) Pivot Shift Grade Grade 0 = -0.1(4.7) Grade 1 = 1.1(6.1) Grade 2 = 3.9(5.27) Grade 3 = 4.1(6.1) Total Translation Acceleration (m/s^{-2} ,SD) Pivot Shift Grade Grade 0 = 0.21 ± 0.12 Grade 1 = 0.25 ± 0.14 Grade 2 = 0.34 ± 0.20 Grade 3 = 0.60 ± 0.33	Not stated	Arthroscopy

			ML translation acceleration (m/s^2) Pivot Shift Grade Grade 0 = -0.02 ± 0.33 Grade 1 = 0.03 ± 0.37 Grade 2 = 0.25 ± 0.50 Grade 3 = 0.84 ± 0.63 AP translation acceleration (m/s^2) Pivot Shift Grade Grade 0 = 0.14 ± 0.07 Grade 1 = 0.17 ± 0.11 Grade 2 = 0.18 ± 0.11 Grade 3 = 0.28 ± 0.15		
Matsushita et al. (2013)(145)	Lachman's	EMS	AP Tibial Translation (mm), ACL ruptured Mean $\pm$ SD = 14.8 ± 3.7 Side-to-side difference in ATT (mm), Mean $\pm$ SD = 4.6 ± 3.6	Not stated	MRI and arthroscopy
	Pivot Shift		Posterior Tibial Translation (APT) Acceleration (m/s^2), Healthy Mean $\pm$ SD = 0.8 ± 0.3 ACL Mean $\pm$ SD = -1.1 ± 0.4		
Nishida et al. (2020)(149)	Pivot Shift	EMS	Tibial acceleration (m/s^2), Mean $\pm$ SD = Time from injury < 3 months = 1.4 ± 0.5 >3 and <6 = 1.4 ± 0.6 >6 and <12 = 1.4 ± 0.5 >12 months = 2.2 ± 1.1 According to meniscal status, < 3 months LM = 2.0 ± 0.7 MM = 1.3 ± 0.4 None = 1.2 ± 0.5 >3 and <6 months LM = 2.1 ± 0.6 MM = 1.2 ± 0.6 None = 1.3 ± 0.5	"The accuracy of the EMS was examined previously. The mean standard deviation of the 3 measurements was $0.2 \pm 0.1 \text{ m/s}^2$, and a difference of 0.5 m/s^2 was assumed to be clinically meaningful."	Arthroscopy

			>6 and <12 months LM = 2.0 ± 0.9 MM = 1.2 ± 0.7 None = 1.3 ± 0.4 >12 months LM = 2.4 ± 1.1 MM = 2.1 ± 1.0 None = 2.3 ± 1.5 Total Tibial Acceleration (ms^{-2}), Mean $\pm$ SD. According to meniscal status, LM Tear = $2.1 \pm 0.8^*$ MM Tear = $1.5 \pm 0.7^*$ None = $1.4 \pm 0.6^*$ Meta-Mean = $1.6 \pm 0.69^*$		
OMC					
Senorski et al. (2018) (148)	Pivot Shift	Optical motion capture	AP Translation (mm), Mean $\pm$ SD. ACL-injured leg = 1.95 ± 1.15 Side-to-side = 1.04 ± 1.35	Not stated	Arthroscopy
Sundemo et al. (2018) (151)	Pivot Shift	Optical motion capture	Tibial Acceleration (ms^{-2}), Median Beighton Score of Joint Hypermobility 0-4 ACL-injured leg = 2.00 Healthy leg = 0.80 Side-to-side difference = 1.00 5-9 ACL-injured = 1.65 Healthy leg = 0.52 Side-to-side difference = 0.83	IMU intra-class correlation 0.79 IAS ICCs >90	Arthroscopy
Svantesson (2018) (96)	Pivot Shift	Optical motion capture	Lateral tibial translation (mm), Mean $\pm$ SD. ACL-injured leg = 2.36 ± 1.80 Healthy leg = 1.20 ± 0.9	Intraobserver and interobserver intraclass correlation coefficient has been reported as >0.90 (154)	Arthroscopy

† - 30lb of force used on arthrometer device, * - value derived from study by calculation
NS, not specified. LM, lateral meniscus. MM, medial meniscus. ATT, Anterior Tibial Translation

4.6.4.2.1. Arthrometer

Eleven studies reported using an arthrometry device to measure dynamic knee instability. Past studies have reported that the average side-to-side difference in ATT in ACL-injured knees ranges from 3mm and 6mm (97). Some arthrometer devices require a specified amount of force applied to the knee (15, 20, or 30lb) to induce anterior tibial translation. In studies where there is no force explicitly stated, it was assumed that a maximum laxity was sought for; this would be produced by applying a maximum force (30lbs) on the arthrometer (97, 155). Whilst arthrometry instruments are able to generate absolute values of ATT on both the injured and uninjured knee, side-to-side differences between knees were most commonly reported due to individual differences between participants (36, 156).

4.6.4.2.2. Inertial Measurement Unit (IMU)

Nine studies were identified that used or incorporated the use of IMU sensors to measure knee instability post-ACL rupture. Berruto et al. 2013 (138) measured acceleration as a maximum and minimum side-to-side difference of tibial acceleration during the pivot shift (ms^{-2}), with results of $0.4 \pm 0.1 \text{ ms}^{-2}$ and $0.5 \pm 0.2 \text{ ms}^{-2}$ respectively to demonstrate knee laxity. Caracciolo et al. 2021 (139) took an acceleration range (maximum – minimum acceleration) as well as side-to-side difference (0.34 ms^{-2}) as a measure of knee laxity. In Labbe et al. (2015) (143), both tibial and femoral acceleration values of knee laxity were detailed according to grades of the pivot shift test, where the highest acceleration ($11.7 \pm 7.3 \text{ ms}^{-2}$) was noted in the tibia in grade 3 pivot shift knees. Muccioli et al. (2018) measured mean side-to-side difference in the range of tibial acceleration ($2.0 \pm 1.0 \text{ ms}^{-2}$) with data classified according to grades on the International Knee Documentation Committee (IKDC) Questionnaire for knee symptoms.

4.6.4.2.3. Electromagnetic Measurement Systems (EMS)

Three studies were identified that used EMS to measure dynamic knee instability. Data outputs from the EMS studies varied greatly. Labbe et al. (2010) (142) measured values of acceleration, magnitude, and velocity during the pivot shift as its outputs (only acceleration and magnitude data were considered under this scoping review). Acceleration values were recorded as mm/s^2 . A maximum total translation (mm) of 16.9 ± 5.4 and total translation

acceleration of 0.60 ± 0.33 were noted as the highest values, both in patients with grade 3 pivot shift (see Table 14 for all values).

Matsushita et al. (2013) (145) recorded outputs of ATT and acceleration of tibial posterior translation and recorded a side-to-side difference of ATT of 4.6 ± 3.6 mm and mean of $-1.1 \pm 0.4 \text{ ms}^{-2}$ respectively. In contrast Nishida et al. (2020) (149) only measured an acceleration output during the pivot shift test, which was stratified according to time-from-injury and meniscal status, therefore a meta-mean of Nishida's values was calculated to yield total tibial acceleration across meniscal status (irrespective of time-from-injury), this produced a value of $1.6 \pm 0.69 \text{ ms}^{-2}$.

4.6.4.2.4. Optical Motion Capture OMC

There were 3 studies that used optical motion capture (OMC) to measure knee instability. Senorski et al. (2018) measured a side-to-side difference of 1.04 ± 1.3 mm using OMC whilst performing the pivot shift test. Sundemo et al. (2018) used the Beighton scoring system and classified generalised joint laxity into the score ranges 0-4 and 5-9 on the 9-point scale. In Svantesson (2018), a side-to-side difference in translation of 1.16mm was calculated (taken from the difference between values measured for the injured and healthy leg).

4.6.4.2.5. Dynamic MRI

Logan et al. 2004 (136) utilised dynamic MRI to analyse ATT. In this study, three measurements were taken (one neutral as a reference point, and the other two with stress applied to displace the tibia anteriorly and posteriorly). The position of the posterior femoral condyles in relation to the tibia were used as measurements of displacement, a mean ATT value of 8.2 ± 1.9 mm medially and 14.1 ± 3.6 mm laterally were recorded.

4.6.5. Discussion

This review scoped the existing literature to comprehend and examine the methods used to assess dynamic knee laxity in people with suspected ACL rupture following knee trauma. There were 19 papers included in this study, these were further stratified to the five main types of technologies recorded across the papers: arthrometry, EMS, MEMS, OMC, and dynamic MRI.

It became evident that there is not an established or consistent protocol in place for quantifying knee laxity, furthermore, there appeared limited consistency in the subsequent

laxity metrics obtained. Studies were also affected by differences in the clinical laxity tests performed with each device. The lack of consensus in both the protocol and outputs obtained is problematic and suggests that there is uncertainty as to what metrics of knee instability should be quantified. The interpretation of knee laxity of this patient cohort is fundamental in the diagnosis of injury, and its management, thus reliable and consistent metrics of knee laxity could facilitate patient care.

Arthrometry devices were the most common device used to assess joint instability, featured in 41% of the studies reviewed. This prevalence may be attributed to their cost-effectiveness relative to other devices, their established history as a research tool, and their ease of use (97, 157, 158). There were, however, notable differences in the approach to using these devices for measurement such as the magnitude of force that is applied to the leg (15lb, 20lb and 30lb) and the form in which measurements are recorded (i.e., either as a discrete measurement of the injured leg, or relatively as a side-to-side difference). Given the arthrometer's popularity as a device of choice over the past years, it has not established itself as a tool to clinically assess knee instability. There also appeared to be a substantial variation in the metrics obtained, despite shared patient population characteristics. Additionally, other than one study by van Eck et al. (2013) who stated the KT-1000 arthrometer sensitivity as 0.93 (69), no other paper commented on the sensitivity or specificity of the arthrometer.

Studies that used IMU devices to quantify knee laxity varied in many ways. Whilst 8 studies measured the changes in acceleration during the pivot shift test, 1 study used the Lachman test. Sensor sampling frequency, number of sensors, and sensor positioning also deviated amongst the literature for studies concerning IMUs and EMS devices. Some studies recorded the values as absolute values as per the patient population whilst others recorded their output as a side-to-side difference between injured and healthy knees. Most papers recorded values as acceleration (m/s^2) however some papers recorded this as translation magnitude; this was the case for both IMU and EMS papers. The heterogeneity between the testing procedure for both EMS and IMU and disparity in recorded values implied a lack of consensus of how to measure knee laxity with this device type.

OMC requires specific marker placement to obtain values of displacement, marker positioning had much variability within the papers. The positioning of marker placement dictates how kinematics of the limbs are calculated; implications of varied marker placement include

variability in anatomical landmark identification, inter-individual differences, skin and soft tissue artifacts, and operator skill (159, 160). These factors can lead to inconsistencies in the calculated kinematics of joints and segments.

Whilst OMC acts as the gold standard for analysing biomechanics, it is limited by high costs, lengthy post processing times and the need to perform testing in a laboratory environment (131, 133). The studies that included OMC assessed translation via the pivot shift test, however whilst one study commented on this laxity in the anterior-posterior plane, another focused on the medial-lateral plane.

Whilst multiple tools exist with the capability to measure aspects of knee laxity, there is variability in both the way in which laxity is measured and the values obtained. The importance of knee laxity is established (7), however the subjectivity surrounding its assessment has a range of implications both for the health service, and the individual. Unnecessary appointments, delayed imaging and investigations, uncertain and inappropriate management, and delayed surgery and rehabilitation all contribute to negative patient outcomes and increased service costs (3, 34, 61).

From the patient's perspective, additional hospital visits have financial implications, as well as frustration and longer time functioning at a lower level due to the delay in reaching appropriate management and care. Delayed diagnosis of ACL injuries can significantly exacerbate the risk of secondary pathologies within the affected knee (161). Meniscal tears, along with subchondral bone and cartilage damage, may develop due to compromised knee mechanics and functionality that persist when an ACL injury is not promptly or accurately addressed (161). These secondary injuries can accelerate the degenerative process, ultimately advancing the onset of post traumatic osteoarthritis (PTOA). (162, 163). Specifically, diagnosing ACL injuries within a four-month window has been associated with a 68% reduction in the risk of medial meniscus injuries (9), a critical factor given that meniscal damages are known to exacerbate the development of PTOA by altering joint mechanics and increasing joint stress. Similarly, ACL reconstruction within six months significantly lowers the likelihood of requiring future meniscal surgeries (164), and surgery within twelve months diminishes the risk of concomitant cartilage damage (165). This directly influences the probability of secondary meniscal injuries, which, if reduced, can significantly lower the long-term risk of developing PTOA.

Hence, the proactive management of ACL injuries through early diagnosis and timely surgical intervention not only addresses the immediate structural and functional challenges but also plays a vital role in preventing secondary meniscal injuries, thereby substantially reducing the progression to PTOA. Prompt and precise diagnosis is therefore crucial in preventing the cascade of joint deterioration that leads to this debilitating condition (163). Furthermore there are psychological impacts on the patient (125), and the influence it has on the patient's part in the shared decision making towards the choice of their management strategy for the ACL injury (166).

4.6.6. Limitations

The limitations of this scoping review should be recognised. Firstly, the considerable heterogeneity among the included studies meant there was a wide array of metrics and tools to quantify knee laxity. This diversity in methodologies made it difficult to synthesise data and draw direct comparisons across studies. Additionally, the review was constrained by the unavailability of full texts for 16 relevant studies, either these texts were not available in English or not available through imperials institution access, requests for texts were made but were unsuccessful. The absence of these texts limited our ability to fully assess the depth and scope of existing research, potentially omitting valuable data that could influence the overall findings and conclusions. As such, the results must be interpreted with caution, acknowledging these gaps in data availability and the variability in study designs.

4.6.7. Conclusion

The knee is a complex joint which can give rise to joint laxity across multiple planes of movement. In order to thoroughly assess and quantify knee laxity to help diagnose ligamentous injury, joint laxity needs to be considered and measured in these 3 movement planes. Whilst there seems to be the technological advancement available to measure such movement, the adoption and accuracy of these into this clinical setting needs to be researched in more detail.

There is a lack of consensus in the both the type of apparatus and its subsequent settings to assess dynamic knee laxity, furthermore, there does not exist a way to reliably assess the instability caused by an ACL rupture that can be performed with ease in a clinical setting. Arthrometry studies had the most published literature but had varied laxity outputs. Papers

using IMUs and EMS systems mainly reported acceleration metrics during the pivot shift test, which there does not appear an agreed metric threshold of injury. OMC systems had varied testing and methodological protocols and are confined to the laboratory environment, they do not provide a clinically viable solution to quantifying knee laxity. Wearable systems should be continued to be investigated in the clinical environment to provide measures of kinematics to joints to explore the utility to provide metrics of knee laxity that can help identify ligamentous injury and personalised biomechanical information.

5. Development of the Methodology for Assessing Laxity with Optical Motion Capture Systems

5.1. Background: Problems Associated with Measuring Laxity

The core aim of this PhD research was to objectively quantify knee laxity during clinical tests, with the goal of defining the movement characteristics of individuals with ACL injuries compared to healthy controls. To achieve this, it was necessary to develop a robust methodology for calculating laxity values using OMC systems. This chapter outlines the steps involved in creating this methodology. It begins by describing the measures taken to minimise soft tissue artefact movement through the development of a custom assessment rig. Next, it details an exploratory study conducted which evaluated the movement of the assessment rig relative to the skin surface; this was calculated as the ‘slippage’ of the assessment rig. The chapter then covers the study setup, participant recruitment, and testing protocols used in the cohort study. Finally, it explains the calibration and analysis processes required to obtain accurate OMC metrics, ensuring reliable assessment of knee laxity across different clinical contexts.

Optical Motion Capture (OMC) is considered the ‘gold standard’ in movement analysis and biomechanics (167, 168). Therefore, OMC analysis was initially utilised to quantify the kinematics of the knee during clinical laxity tests in both ACL-injured patients and healthy controls. OMC systems provide the ability to measure detailed measures of knee laxity in all planes of motion.

Many clinical tests are widely used to assess ligamentous knee integrity, but their application varies significantly. Some clinicians prefer specific tests, while others use a broader range, with tests performed only once. This study aimed to enhance clinical protocols for knee injury assessment by using OMC analysis to capture detailed laxity measurements during these tests. Established clinical tests, such as the anterior drawer and Lachman test, were used in this protocol, as well as novel unpublished variations of these clinical tests, such as the anterior drawer performed while sitting on the edge of the bed and the Feagin-Thomas test.

Rotational laxity and laxity across multiple planes of movement are often overlooked in clinical assessments, yet they are crucial for identifying concomitant injuries and understanding overall knee functionality. This research introduces a novel application of OMC

systems to measure joint laxity with high precision, particularly within the anterior and rotational axes. The study further explores how various factors influence laxity, offering new insights into knee functionality that can inform clinical assessments.

While OMC systems are invaluable for capturing detailed kinematic data, they are not without limitations, particularly their susceptibility to soft tissue artefact movement(96, 148, 151) (169). To effectively measure knee laxity, it was essential to minimise these artefacts. To address this challenge, a custom assessment rig was designed and 3D-printed. The criteria of the design were that it was securely fitted and anchored onto the bony landmarks of the limb whilst ensuring an assessor could handle the limb during clinical tests so that they could be conducted effectively.

The marker and sensor setup, along with the OMC calibration processes, participant recruitment, ethical approvals, and testing protocols, form the foundation of the cohort study detailed in this research. Data collection was designed to be completed in a single session, ensuring consistency across all tests. The methodology presented in this chapter is relevant to the subsequent analysis discussed in Chapters 6-9, where the results from the various sensors, including OMC, EMG, and IMUs, are explored. Finally, this section also outlines the data processing and analysis techniques used to derive accurate OMC metrics, which are critical for quantifying knee laxity and interpreting the outcomes of clinical tests.

Research Question:

How can knee laxity in different planes be accurately calculated using Optical Motion Capture (OMC) systems while minimising measurement errors?

Sub-Questions:

What strategies or tools can be employed to minimise soft tissue artifact movement during knee laxity measurements with OMC systems?

What is the error of the 3D assessment rig relative to the surface of the skin and what is the effect on knee laxity measurements?

How can a standardised protocol and marker setup be developed for OMC systems, EMG sensors and IMU sensors, that replicates a comprehensive examination of knee laxity and ensures accurate measurements across different planes of motion?

5.2. Methods

5.2.1. Assessment Rig Build

The assessment rig was designed and inspired based of a system called the KneeKG (170); this system was designed to reduce soft tissue artefact movement and increase the reliable collection of kinematic knee data. A review found by using this system, more accurate metrics of knee laxity could be calculated with OMC (171) (see paper for image of KneeKG system).

The assessment rig was designed such that it could be fixed to the leg and adjusted to the individual using velcro straps. There were 4 components to the device: a femoral arc, femoral anchor shafts, a femoral cluster slider and the tibial assessment rig. Different sizes of the femoral arc were produced to accommodate a range of participant sizes [Figure 16]. The femoral arc of the model included 5 different contact points along the distal femoral shaft, as well as 2 anchor shafts which ran medially and laterally along the femoral segment [Figure 12]; these were created to reduce slippage of the model on the leg and ensure optimal fit [Figure 15]. Different anchor shaft sizes were tried and tested to allow for optimal secure positioning whilst allowing for comfort [Figure 17]. Likewise, the tibial component of the model was created so it could be anchored against the anterior surface of the tibial shaft [Figure 13]. The IMUs were secured on the VICON clusters, of which there was a cluster for both the femur and tibia, these were secured with a slider [Figure 14].

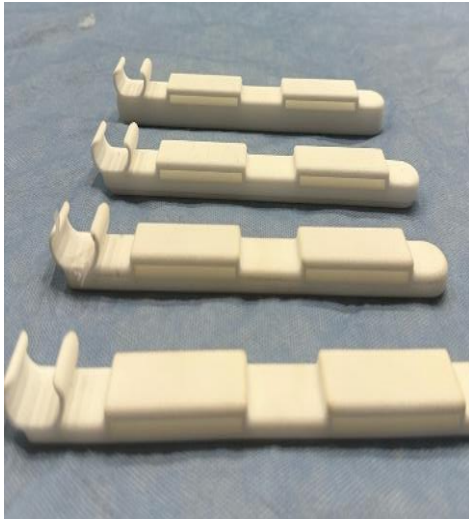


Figure 17: Different Femoral Anchor Sizes



Figure 16: Different Femoral Arc Sizes

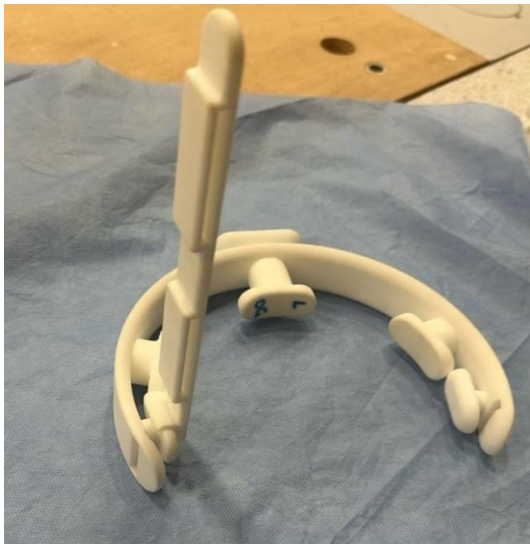


Figure 15: Femoral Anchor to Arc Attachment

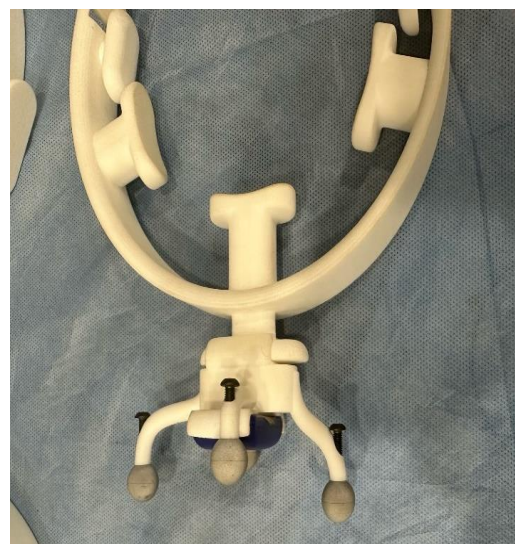


Figure 14: Cluster attachment to Arc



Figure 13: Tibial Assessment Rig



Figure 12: Femoral Assessment Rig

5.2.2. Methods of Calculating Assessment Rig Slippage

An exploratory study was conducted to establish the 'slippage' with an adapted version of the marker set up. The 'slippage' was the movement of the assessment rig relative to the skin's surface. To calculate the slippage during laxity tests, the three clinical tests assessing ATT as part of the cohort study (Lachman, anterior drawer and anterior drawer sat on the edge of the bed) were repeated, custom MATLAB scripts were then used to process the data and calculate the slip. This was repeated on 2 subjects, one was a healthy control subject, and one was an ACL injured participant.

The marker set remained the same as documented in section 5.2.5, however, a few additional static single markers were added as seen in [Figure 18 and Figure 19]. The single markers directly on the skin were then used as the anchor on the segment to calculate the cluster slippage.

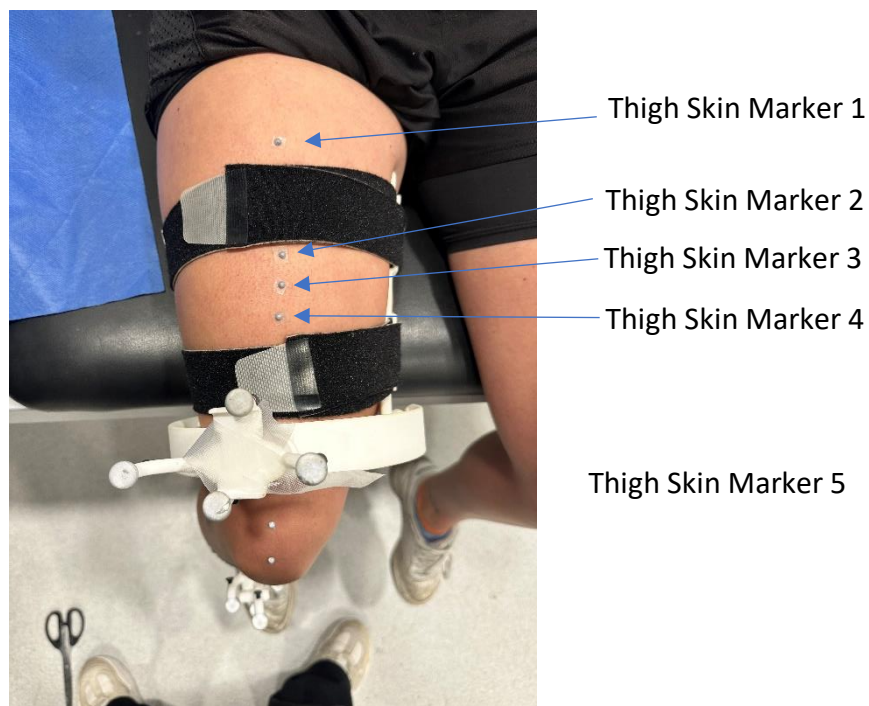


Figure 18: Additional Femoral Marker Placement to Calculate Assessment Rig Slippage

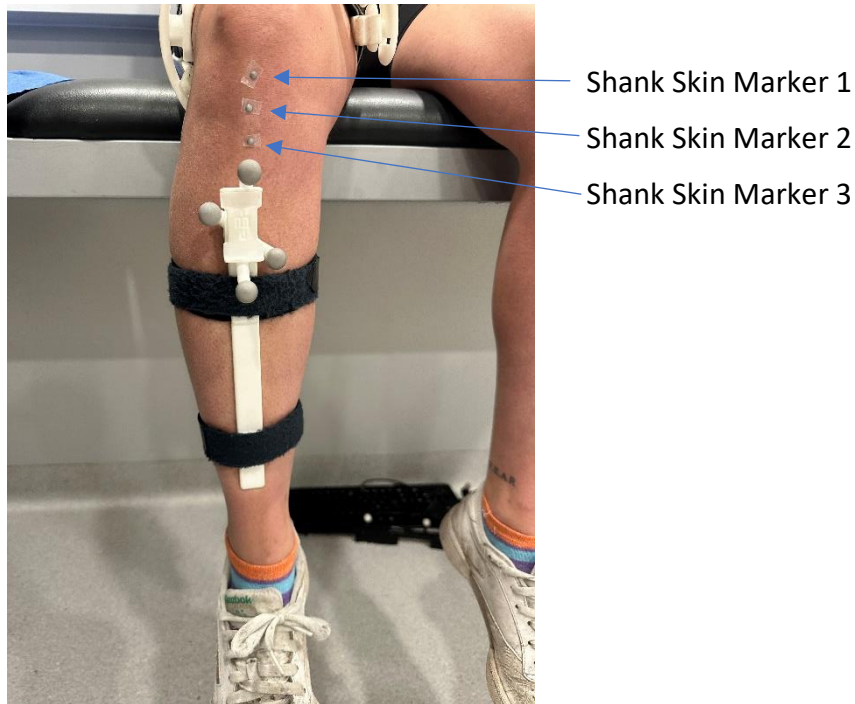


Figure 19: Additional Tibial Marker Placement to Calculate Assessment Rig Slippage

The Anterior Drawer and Lachmans test were performed as normal and are described in section 5.2.14. The ADSOEOB test is also described in this section, for this exploratory study investigating the rig slippage, two variations of this test were completed. The first variation ensured the femur was in contact with the bed (ADSOEOB low) and the second was listed slightly off the bed (ADSOEOB high). This was because when performing the test in the lab during the cohort study, there was suspicion that when the leg was in contact with the bed the femur was being moved relative to the rig.

The slippage was the movement of the respective cluster on the associated segment. For example the the movement on the femoral cluster relative to the skin of the femur (Which was obtained from a one of the small markers which was situated directly on the skin). The slippage was calculated as a distance in mm measuring the difference of the translation obtained when using the rig cluster as the reference point and when using the individual skin marker as a reference point [Figure 21 and Figure 20].

Fem Slippage = Femoral cluster translation (mm) along femoral axis
 – Skin marker translation (mm) along same femoral axis

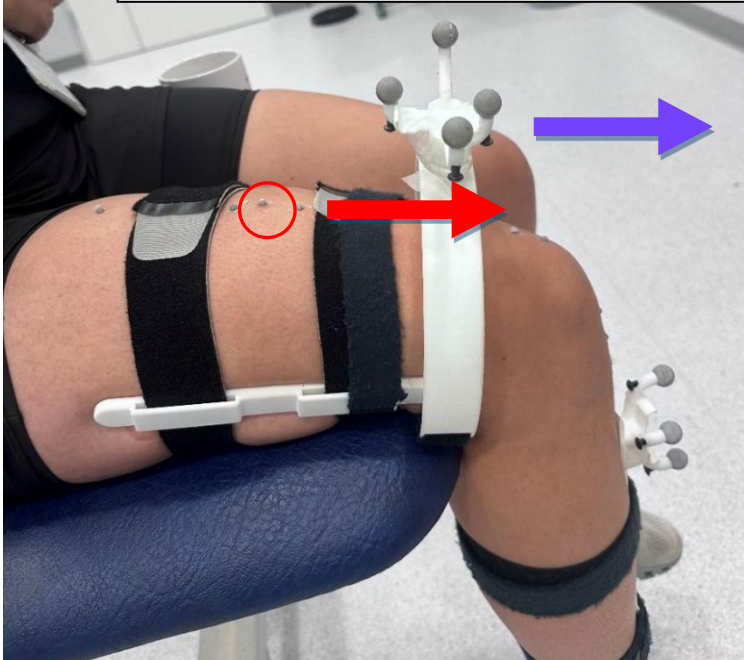


Figure 21: Diagram explaining Femoral Slippage

Tib Slippage = Tibial cluster translation (mm) along tibial axis
 – Skin marker translation (mm) along same tibial axis

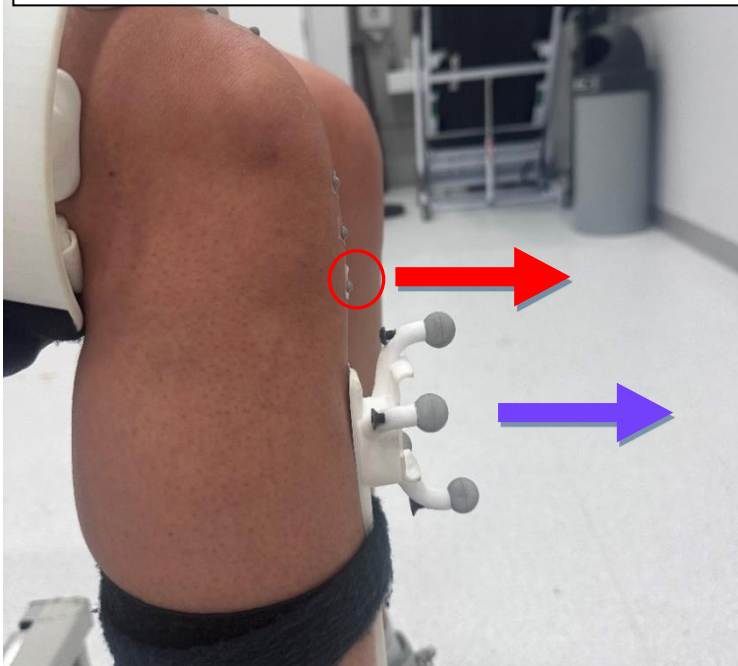


Figure 20: Diagram Explaining Tibial Slippage

The individual skin marker was chosen as skin marker 3 for the femur [Figure 21] and skin marker 3 for the tibia [Figure 20]. These were chosen as these markers provided the cleanest data for the trials with minimal marker occlusion.

The ATT was recorded and then percentages were subsequently calculated which was the amount of slippage (mm) divided by the amount of ATT to get a representation of how much translation was resultant from soft tissue movement rather than bony translation.

$$\% \text{ of slippage} = \frac{\text{Slippage of relative segment}}{ATT \text{ (mm)}}$$

The femoral slippage is then a representation of how much overall ATT (mm) is likely due to the the femoral rig is moving relative to the skin. The tibial slippage is a representation of how much overall ATT (mm) is likely due to the the tibial rig is moving relative to the skin.

5.2.3. Results: Calculating Assessment Rig Slippage

As demonstrated in and Table 15 and Table 16, there is movement of the femoral and tibial clusters during clinical testing. ATT is higher across all tests in the ACL injured participant in comparison to the healthy. Both the femoral and tibial slippage (mm) is also larger across all clinical tests in the Injured participant. However, the slippage (%) of the tibia and femur is not higher in the injured participant in comparison to the healthy across all clinical tests, this is due to the way in the % is calculated; the relative translation should be noted.

In the healthy subject, the tibial slippage (%) was particularly high (91.6%) in the anterior drawer test. Within the healthy subject, the tibial slippage (%) in general is larger than the femoral for the anterior drawer and Lachman test. However the two variations of the ADSOEB test show higher femoral slippage in comparison to tibial (%). In the injured subject, the tibial slippage (%) was consistently higher than the femoral across all clinical tests. Tibial slippage (%) appears highest in the AD test, followed by the ADSOEB high, then ADSOEB low and finally the Lachman test across both participants.

Table 15: Femoral and Tibial Slippage of Assessment Rig on Skin Calculated in mm, the relative ATT during the Clinical Test Performed, and a % Slippage calculated as the Slippage (mm)/ Relative Translation for A Healthy Control Subject

Healthy Control Subject	Fem Slippage (mm)	Relative Translation (ATT) (mm)	Fem Slippage (%)	Tib Slippage (mm)	Relative Translation (ATT) (mm)	Tib Slippage (%)
Ant Drawer	0.96	3.09	31.0%	2.83	3.09	91.6%
Lachman	1.05	7.16	14.7%	1.47	7.16	20.5%
ADSOEOB Low	4.20	10.37	40.5%	2.44	10.37	23.5%
ADSOEOB High	2.92	9.13	32.0%	2.70	9.13	29.6%

Table 16: Femoral and Tibial Slippage of Assessment Rig on Skin Calculated in mm, the relative ATT during the Clinical Test Performed, and a % Slippage calculated as the Slippage (mm)/ Relative Translation for ACL Injured Subject

ACL injured Participant	Fem Slippage (mm)	Relative Translation (ATT) (mm)	Fem Slippage (%)	Tib Slippage (mm)	Relative Translation (ATT) (mm)	Tib Slippage (%)
Ant Drawer	1.23	9.50	12.9%	4.80	9.50	50.5%
Lachman	1.92	11.17	17.2%	2.27	11.17	20.3%
ADSOEOB Low	5.16	26.06	19.8%	6.80	26.06	26.1%
ADSOEOB High	4.61	22.39	20.6%	7.81	22.39	34.9%

5.2.4. Assessment Rig Discussion

Both femoral and tibial clusters we seen to move relative to the skin markers. This means that the there was some internal play between the skin and the clusters. This section is reviewing the ability of the setup to evaluate the movement of the assessment rig on the skin's surface.

Skin movement occurs due to the natural presence of soft tissue between the skin and the underlying bone. When external forces are applied during clinical tests, the soft tissues, including muscles, tendons, and fat, can shift, causing the skin to move independently of the bones. In dynamic tests such as those assessing knee laxity, the skin may slide or stretch, especially in areas with less direct contact to bony landmarks.

The movement of the cluster relative to the skin indicates that there is some "slippage" between the skin and the marker cluster, which could introduce error into the assessment of actual bone movement. However, this movement does not necessarily imply that the rig is not accurately reflecting the motion of the underlying bone. The assessment rig, being anchored to bony landmarks, might move in concert with the bone itself, while the skin moves independently. Therefore, slippage between the skin and the cluster may overestimate the actual error in measuring bony movement This means the rig could still provide an accurate measure of bony translation despite the skin-cluster movement.

The tibial slippage as a percentage was higher than that of the femoral slippage for both the injured participants for the 4 variations of clincial tests. This indicates that there is more of a discrepancy between the tibial cluster and the 3D printed tibial assessment rig than that of the femur. It was also higher for the healthy participant for the anterior drawer and Lachman test, whereas the femoral slippage (%) was higher for the 2 variations of the ADSOEOB test.

The slippage as a percentage was much greater in the healthy control participant than that of the injured, this relates to the fact that the amount of laxity induced in the injured participant is higher than that of the healthy control, so the relative slippage of the rig as a percentage has less of an impact on larger measures of translation (in mms).

The two variations of the ADSOEOB test yielded very similar slippage outputs, both as a percentage and as a distance (mm). This suggested that the limb was not moving relative to the rig as we suspected when the femur was in contact with the bed.

The rig was designed to anchor onto superficial bony landmarks to minimise the effects of soft tissue movement on measurements. While slippage should be taken into account, it is important to note that slippage was measured as cluster movement relative to the skin. The skin, however, is not necessarily a more accurate reflection of bony movement than the assessment rig itself. Therefore, although the slippage data provides insights into how the rig moves relative to the skin, it does not directly indicate the rig's measurement error concerning true bony translation. It is possible that the rig moves in concert with the bone, while the markers placed on the skin shift due to soft tissue movement. However, bony structural movement is difficult to quantify non-invasively.

Although some postulate that actual bony translation could be obtained with either dynamic MRI or intraoperative measurements, both have limitations. Dynamic MRI often suffers from poor image quality during manual stability tests, mainly due to the lower Tesla strength used in such scenarios which require an 'open-MRI' approach (137, 172). Measuring bony translation during surgery also has its drawbacks, as it typically occurs under anaesthesia, which eliminates factors such as muscle activity and patient apprehension—conditions not reflective of standard clinical testing for ACL integrity. Despite these challenges, this validation study quantified how the rig moves relative to the skin, helping to evaluate the potential error sources in our measurements.

5.2.5. VICON camera set-up

To determine body kinematics and kinetics, a 28-camera optical motion tracking system was used (Vicon, Oxford, UK) (Figure 1). The infra-red cameras were arranged around the laboratory and captures the three-dimensional trajectories of 14mm diameter reflective markers detailed below. Vicon Nexus software will be used to record and reconstruct marker positions.

5.2.6. Cohort Study Marker Setup

Skin exposure of the lower limb was necessary in order to secure relevant optical motion capture markers, the assessment rig, and EMG sensor placement. The femoral rig was secured so that the anchor shafts were secure on the medial and lateral femoral shaft, the base of the rig sat about 2.5 inches above the apex of the patella, the straps were tightened so that it was secure against the mid portions of the femur [as seen in Figure 23 and Figure 22]. Additional single Vicon markers were distributed to the foot and ankle [Table 17].

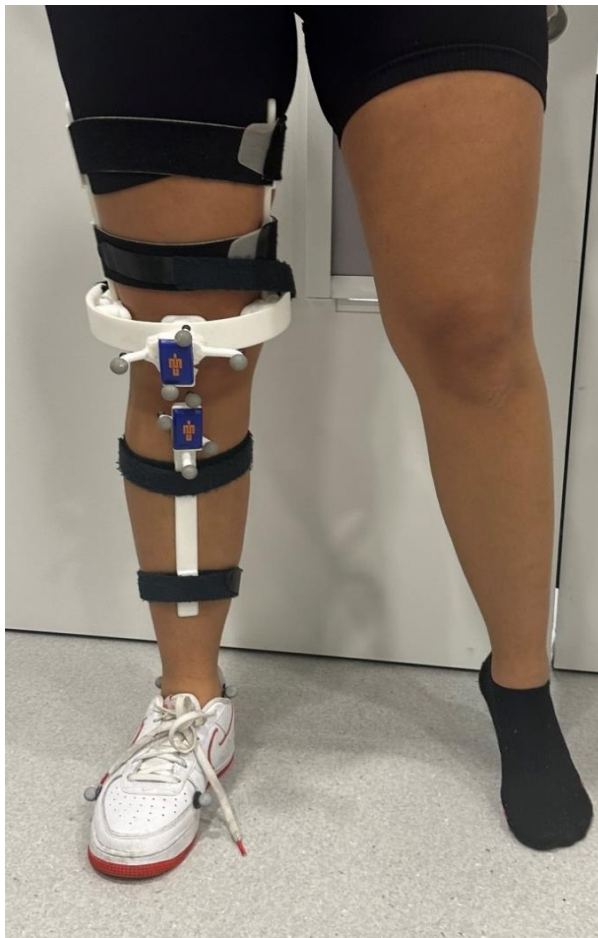


Figure 23: Anterior View of Marker Set up

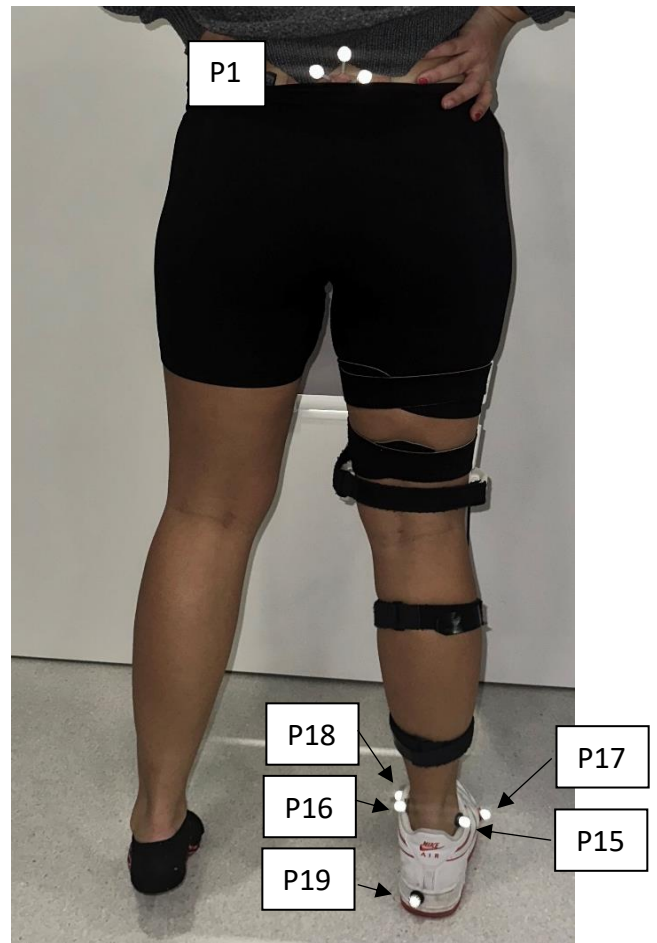


Figure 22: Posterior View of Vicon Marker Setup

Anatomical Abbreviations:

- ASIS: Anterior Superior Iliac Spine
- PSIS: Posterior Superior Iliac Spine
- Fem: Femoral
- Tib: Tibial
- Epi: Epicondyle
- Con: Condyle
- Med: Medial
- Lat: Lateral
- TibTub: Tibial Tuberosity

Table 17: Vicon Marker Anatomical Set-Up

VICON marker anatomical set up				
Segment	Marker (static)	Probed point	Marker label	Location
Pelvis	Pelvis	-	P1	Marker Cluster between L5 and S1
	-	ASIS L	P2	Left Anterior Superior iliac spine
	-	ASIS R	P3	Right Anterior Superior iliac spine
	-	PSIS L	P4	Left Posterior Superior iliac spine
	-	PSIS R	P5	Right Posterior Superior iliac spine
Femur	Femoral Cluster	-	P6	Femoral cluster fixed to femoral 3D printed model and is attached to Distal femoral condyle and attached via Velcro straps
	-	FemEpiMed	P7	Medial femoral epicondyle
	-	FemEpiLat	P8	Lateral femoral epicondyle
	-	FemMedCon	P9	Multiple probe points are made along the distal medial femoral condyle
	-	FemLatCon	P10	Multiple probe points are made along the distal Lateral femoral condyle
Tibia	Tibial Cluster	-	P11	Tibial cluster fixed to tibial 3D printed model. Model is attached tibial shaft and attached via Velcro straps
	-	TibMedEpi	P12	Medial tibial epicondyle
	-	TibLatEpi	P13	Lateral tibial epicondyle
	-	TibTub	P14	Tibial tuberosity
	Lateral Malleolus single marker	-	P15	Lateral Malleolus

	<i>Medial Malleolus single marker</i>	-	<i>P16</i>	<i>Medial Malleolus</i>
<i>Foot</i>	<i>Base of 5th Metatarsal single marker</i>	-	<i>P17</i>	<i>Base of 5th Metatarsal</i>
	<i>Base of 1st Metatarsal single marker</i>	-	<i>P18</i>	<i>Base of 1st Metatarsal</i>
	<i>Posterior Calcaneus Mid-point single marker</i>	-	<i>P19</i>	<i>Posterior Calcaneus Mid-point</i>

5.2.7. EMG Sensor Setup

Three Surface EMG sensors (Trigno system, Delsys Inc., Natick, MA, USA), sampling at 2,000 Hz, were placed over the muscle belly of the rectus femoris, medial hamstrings, and medial head of gastrocnemius, these are the three large muscle groups surrounding knee used to assess ‘muscle guarding’ [Table 18 and Figure 24]. The skin was shaved and cleaned with an alcohol wipe where the sensor had contact with the skin.

Table 18: EMG Sensor placement

EMG sensor placement		
Segment	Marker label	Location
Thigh	<i>P20</i>	<i>Rectus femoris Muscle belly (5 inches above apex patella)</i>
	<i>P21</i>	<i>Semi tendinosis muscle belly (4 inches below posterior joint line)</i>
Shank	<i>P22</i>	<i>Medial head of gastric 2.5 inches below joint line</i>



Figure 24: EMG placement secured by K-Tape with Assessment Rig in Situ

A: Anterior view B: Posterior view. Following skin treatment, wireless surface EMG sensors (Trigno™ Avanti) placed on the rectus femoris (quadriceps), semitendinosus (hamstring), and medial gastrocnemius, and secured with double-sided and K-tape.

5.2.8. IMU Sensor Setup

Inertial measurement units (IMUs) (Blue Trident, Vicon Motion Systems Ltd., Oxford, UK), sampled at 225 Hz and then up-sampled to 2,000 Hz to synchronize with the VICON system, were secured into the assessment rig, as shown in, as shown in Figure 24 and Table 19.

Table 19: IMU Sensor Placement

IMU sensor placement		
Segment	Marker label	Location
Thigh	P24	Centrally mounted on the femoral rig to remove from handling site
Shank	P25	Centrally mounted on the tibial rig to remove from handling site

5.2.9. Knee Model Calibration



Figure 25: Calibration Probe

This calibration probe [Figure 25] was used to digitise anatomical points on the limb. The digitised points corresponded to the exact locations where the tip of the probe contacted specific bony landmarks. These points utilised the cluster markers as reference points, offering a distinct advantage when locating points near the articulating surfaces of joints. By allowing deeper penetration into the soft tissue, the probe could locate bony landmarks more accurately than surface markers placed on the skin. Additionally, the digitisation process ensured that these landmarks were not affected by marker occlusion.

The long axes of the femur and tibia were determined using the digitised probe points, which facilitated the identification of the joint centres based on these axes. By defining the medial and lateral femoral epicondyles with the probe, the epicondylar axis of the femur was established. This process was similarly applied to the tibia by defining its epicondyles, allowing for the establishment of reference frames for both bones.

Following this, the articulating surfaces of the femur and tibia needed to be identified. To do so, the participant was positioned at the edge of a treatment plinth with the knee flexed to 90 degrees, which exposed the distal aspect of the condyles. The examiner then used the calibration probe to map the medial condyle by moving along the distal edge of the femoral condyle in 0.5 cm increments, starting just medial to the apex of the patella and continuing posteriorly. This procedure was repeated for the lateral femoral condyle, beginning just lateral to the apex of the patella. Using this method, the most inferior points on the distal

femoral condyles were identified for both the medial and lateral condyles [Figure 26]. This is demonstrated on the sawbone model [Figure 26] and on an actual participant [Figure 27].

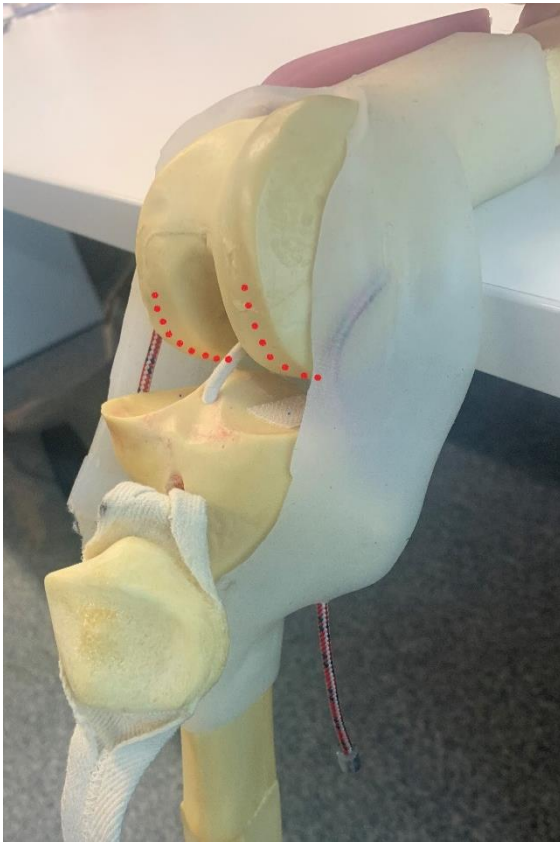


Figure 26: Probed points on most inferior point on medial and lateral femoral condyles.



Figure 27: Probed points on most inferior point on femoral condyles, practical participant application.

Next, the dynamic contact point of the joint was defined as the deepest point of the tibia and how this articulates over the femoral condyle through an active range of motion. The deepest point of the tibia could not be directly probed and was therefore defined using a virtual marker. This point was defined by taking the closest point between a line of best fit for the femur probed surface and the tibial epicondylar axis during a passive full extension trial [Figure 28].

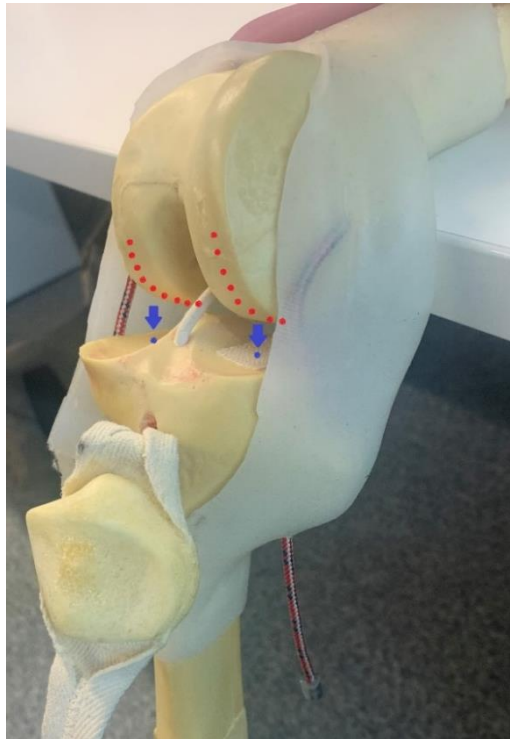


Figure 28: Traced points on tibial plateau

Using the virtual tibial plateau deepest point, the contact of this point onto the femur was dynamically defined from a trial involving the full range of motion of the knee. While the multiple probe points on the femoral condyles help identify the most distal point of the femur, these points do not necessarily reflect contact points with the tibia. The tibial virtual tracing method was used to track how the knee flexes and extends to locate the relative point on the femur [Figure 29]. Anterior tibial translation was defined from the distance between the virtual deepest tibial point and traced femoral contact point. This calculation is dynamic and accounts from changes in knee angle.

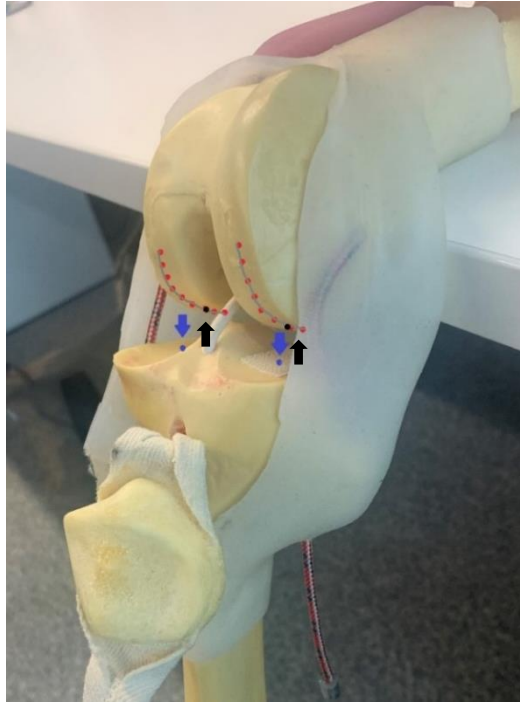


Figure 29: Traced back femoral articulating surface shortest distance point.

The 'shortest distance points' relative to the medial and lateral femoral condyles were then identified [Figure 31]. This is a dynamic distance of the tibial point with the traced surface. If this is 0 then the point is at the same point as the dynamic range of motion trial. Other than this is the translation that was made relative to the tibial reference frame. These points represent the locations on the femur and tibia that are closest to each other, making them crucial for assessing anterior displacement on either side of the knee. This is particularly important for detecting asymmetrical anterior laxity or rotary laxity. Additionally, identifying the medial and lateral points was essential for calculating the midpoint of the knee, which is the halfway point between the medial and lateral shortest distance points. This midpoint is critical for observing changes in direct anterior translation of the knee joint [Figure 30]. Sections 5.3.5 and 5.3.6 explain how these calculations were made.

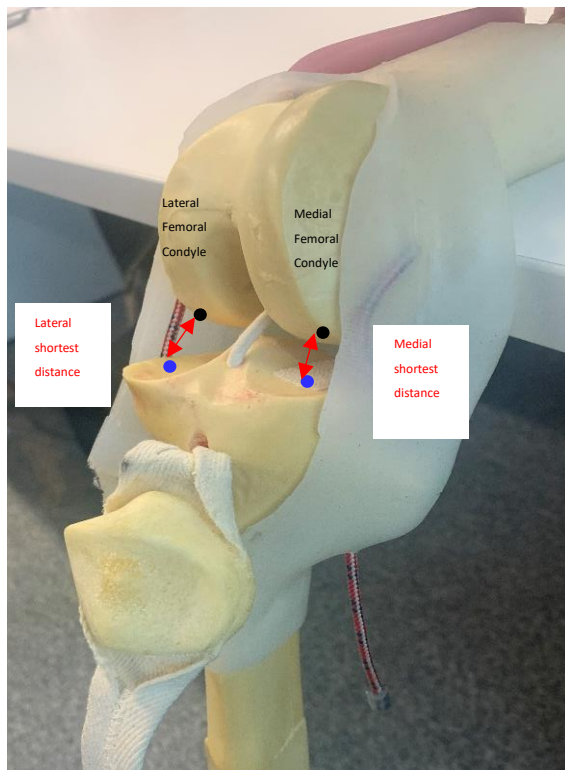


Figure 31: Shortest distance calculated from the two closest articulating surface points.

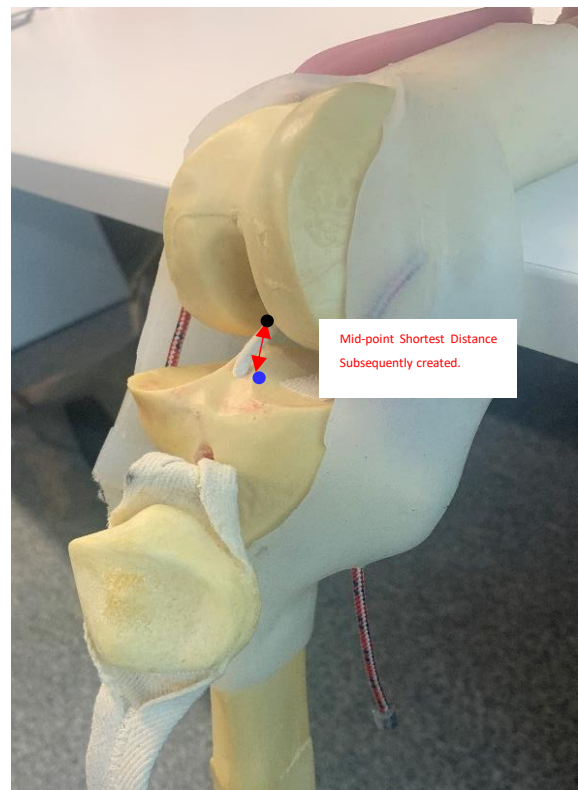


Figure 30: Midpoint Created and Shortest Distance (Anterior Tibial Translation)

5.2.10. Study Population and Recruitment

The study population included participants with ACL injuries and healthy controls with no knee injuries. A recruitment target of 50 participants was set, with 25 ACL-injured and 25 healthy controls. This target was based on power calculations from a previous gait analysis study investigating pivot shift avoidance in chronic ACL injuries(173). The study used VICON to analyse terminal stance phase differences between ACL-deficient and control groups, where mean minimum flexion angles were 1.8° and 5.6° , with standard deviations of 3.8 and 4.9, respectively. With an alpha of 0.05 and power of 0.8, the calculated sample size was 44 participants (22 per group).

To account for potential participant loss and variability, a 10% increase was added to the power calculation to account for any heterogeneity, particularly given the inclusion of acutely injured subjects, the sample size was increased to 50 (25 per group).

Participants were recruited from the Imperial Sports and Exercise Medicine Clinic at Charing Cross Hospital. Patients who met the inclusion exclusion criteria who had MRI confirmation of ACL injury were approached to participate in the study. Healthy participants were recruited

through local networks associated with the Trust and University and through social media. Testing was conducted at the Biodynamics Lab in White City.

5.2.11. Patient Inclusion/Exclusion Criteria

Injured participants were included in the knee injury if they had the following:

- Experienced an acute knee injury and have been referred to the STIM clinic or Fracture Clinic.
- Able to weight-bear on the injured leg.
- Had a confirmed ACL injury verified by MRI.

Injured participants were excluded from the study if they had the following:

- Were aged less than 18 years old.
- Had a chronic joint condition.
- Were allergic to adhesive materials.
- Were unable to weight bear.
- Unable to speak English sufficiently enough to give informed consent to participate.
- Were pregnant- due to gait and laxity changed in the joints, this was ascertained verbally.
- Were aged of 45 years since this posed an increased risk of OA.

5.2.12. Control Subject Inclusion/Exclusion Criteria

Healthy control subjects were included in the study if they had the following:

- Aged 18 and over.
- No history of previous knee ligamentous injury.

Healthy control subjects were excluded from the study if they had the following:

- Were aged less than 18 years old.
- Had a history of previous ACL reconstruction on the injured leg.
- Had a chronic joint condition.
- Were allergic to adhesive materials.
- Were unable to weight bear.
- Unable to speak English sufficiently enough to give informed consent to participate.

- Were pregnant- due to gait and laxity changed in the joints, this was ascertained verbally.
- Participants were aged over 45 years since this posed an increased risk of OA.

5.2.13. ACL Injury Verification Methods

5.2.13.1. Laxity Verification

Currently there is no clinically viable approach to quantifying knee joint laxity (12, 13). Arthrometers have historically been popular in measuring AP laxity within the knee, the KT1000 was a popular type of arthrometer which has greater variability in the reported accuracy and reliability (14, 15, 16, 17). This device has been discontinued and is no longer available to purchase and use. The Lachmeter is another arthrometer device which has been verified against the KT1000 and provides an instantaneous numeric value (mm) of anterior translation whilst the Lachman's test is performed, both the KT-1000 and the Lachmeter use a cut of value of 3mm side-to-side difference to indicate ACL injury (174). For this reason, it was used to compare readings of translation obtained using the Vicon system.

5.1.1.1. Clinical Diagnosis Verification

All participants with knee injury included in our study had an MRI completed as part of their standard care. This is the gold standard for ACL and knee ligamentous injury diagnostics. MRIs are reported by a specialist MSK radiologist and using these reports the knee injury was further classified according to the extent and severity of soft tissues injury.

The soft tissue structures which were categorised as per their morphology were the following:

- ACL
- Deep MCL
- Superficial MCL
- LCL
- PCL
- Lateral Meniscus
- Medial Meniscus

The ligamentous structures were coded as not affected, partially torn, or totally ruptured. The menisci were either coded as not injured/torn or injured/torn. The coding of the morphologically affected structured allows for sub-grouping of the injured structures, the

biomechanical outputs from the various clinical and functional tests were assessed against their MRI findings to help develop a threshold of pathological laxity and to clinically verify the biomechanical findings.

5.2.13 Ethics

Ethical approval was sought and granted prior to the recruitment of participants. This study involved the involvement of NHS ACL injured participants and healthy control subjects. The study was approved by London - Westminster Research Ethics Committee on the 11.08.22 (REC reference: 22/LO/0464 Protocol number: 22CX7532 IRAS project ID: 305240). Imperial College London were the Sponsor for the study (Reference number: 22CX7532).

5.2.14 Protocol

Joint laxity was measured during routine clinical tests and assessments, performed by a clinician, gait analysis was also conducted (Chapter 7). Data was collected simultaneously with the Vicon OMC system (Oxford Metrics, Oxford, UK), EMG sensors (Delsys, Massachusetts), and the wearable IMU sensors (Blue Trident, Vicon, Oxford) for both population groups.

The assessments were performed in the motion capture lab. Motion capture was used to collect kinematic data, IMU sensors collected surrogate markers of knee laxity using accelerometer and gyroscope components, EMG electrodes captured data from the muscle activity of the quadriceps, hamstrings and gastrocnemius.

Prior to the arrival of the subject, the lab was set up and the cameras were calibrated to the workspace and the markers prepared. Informed written consent was obtained and the participant was asked to change into shorts.

The participant was then prepped, the assessment rig which contained the fixed Vicon Marker clusters and the IMU sensors was fitted onto the limb, additional VICON markers and EMG sensors were then attached to the limb as shown in chapters 5.2.5, 5.2.7, and 5.2.8 .

A static calibration task was performed with the participant standing as still as possible at the centre of the capture volume in T-pose for 30 seconds. This allowed the optical motion software to calculate the positions of the markers on the participant.

The participant underwent the following testing:

- **Lachman's Test:** *Anterior tibiofemoral laxity* - The participant lies supine on a treatment plinth with their knee flexed at 20 degrees. They are instructed to relax while the clinician stabilizes the femur and swiftly moves the tibia anteriorly. This movement assesses for increased anterior translation of the tibiofemoral joint and evaluates the joint's end-feel. To obtain quantitative measurements of knee instability, the test is repeated using an arthrometer attached to the tibia, serving as the clinical standard.
- **Anterior Drawer test:** *Anterior tibiofemoral laxity* – The participant lies supine on the treatment plinth with their knee flexed at 90 degrees. They are asked to relax as the clinician sits on the participant's foot and grips the tibial condyles. The clinician then gently pulls the tibia anteriorly to assess increased anterior translation of the tibiofemoral joint and to evaluate the absence of joint 'end feel'.
- **Anterior Drawer Test Seated on Edge of Bed (ADSOEOB):** *Anterior tibiofemoral laxity* – The participant sits on the edge of the treatment plinth with their feet unsupported. The assessor, positioned in front of the participant, grips the proximal tibial condyles just below the knee joint. Using their lower leg to stabilize the participant's foot and maintain a 90-degree knee bend, the assessor then draws the tibia anteriorly relative to the femur to assess for increased anterior translation and joint end-feel.
- **MCL test:** *Valgus tibiofemoral laxity* - The participant lies supine on the treatment plinth. The assessor slightly abducts the participant's hip while stabilizing the knee. The assessor's body aligns against the lateral side of the participant's leg, with one hand positioned medially above the femoral condyle and the other arm wrapping around to support the lateral side of the proximal tibial condyle. The elbow rests firmly against the medial malleolus to act as a lever. Using this setup, a valgus force is applied to the knee. The test is conducted at both 0 and 30 degrees of knee flexion.
- **LCL test:** *Varus tibiofemoral laxity* - The participant lies supine on the treatment plinth with the hip slightly abducted. The assessor positions themselves inside the participant's leg, standing close to the bed. The assessor aligns their body against the medial side of the leg, placing one hand laterally above the femoral condyle and wrapping the other arm around to support the medial side of the tibial condyle. The elbow rests firmly against the lateral malleolus. Using the top hand to stabilize the

medial side of the knee joint, a varus force is applied to the knee. This test is performed at both 0 and 30 degrees of knee flexion.

- **Feagin-Thomas test:** *Anteromedial rotational tibiofemoral laxity* - The participant is sat on the edge of the treatment plinth with the lower limbs unsupported. The assessor stands in front of the patient holding the participant's proximal tibial condyles firmly, the assessors' hands are placed directly below the tibial joint line on the medial and lateral tibial condyles, the assessor then pulls the hand holding the medial tibial plateau anterolaterally whilst trying to stabilise the hand holding the lateral tibial plateaus. The assessor is using their own lower leg to block the foot/shin to maintain a 90 bend in the participant's knee.
- **Reverse Feagin-Thomas test:-** *Anterior lateral rotational tibiofemoral laxity* the above is repeated however the lateral side of the tibial plateau is pulled in an anteromedial direction whilst the medial tibial plateau is stabilised.

Participants are then assessed on their active and passive range of movement (AROM and PROM).

- **AROM-** Participant are supine and are asked to straighten and bend their knee.
- **PROM-** Participant are supine, the clinician will bend and straightens their knee.

Participants were then asked to complete the following functional movements:

- **Linear Walking trials** - A walking trial that consists of walking to the end of the motion analysis walkway (6m) over the floor embedded force plates and back to the starting position was completed.
- **Squat** (progressing to single leg if capable) - Participant stand shoulder width apart in front of a chair with a 90-degree standardised seating position. They are asked to squat until they nearly touch the chair and then stand up again if able. They are asked to progress this to a single leg squat if able.

Fatigue or pain can be an issue with testing, consequently testing was modified as needed for each participant and documented accordingly, and participants were allowed time to rest between tests as required.

While this list demonstrates all the clinical tests performed on participants and the functional tasks they were asked to perform, not all tests were included in the final analysis due to being beyond the scope of this PhD. Future research should consider analysing data sets from all clinical tests.

5.3 Analysis: Optical Motion Capture Data and Calculating Laxity

5.3.1 Data Labelling and Cleaning

Motion capture data was reconstructed, labelled and gap filled using Vicon Nexus 2.15 software (Oxford Metrics, Oxford, UK). Due to the bespoke anatomical marker set up, a custom Vicon labelling Skeleton Template was made within Nexus for the specific marker set up used in this study.

5.3.2 Data Calibration and Processing

Once all trials were reconstructed, labelled and gaps were filled using the appropriate filling technique depending on the number of missing markers and length of gap, calibration and processing scripts were run using custom MATLAB scripts (Mathworks, Natick, Massachusetts). The calibration process allowed the digitised points defined by the probe to map the articulating surfaces of the knee so that detailed measures of laxity could be calculated.

Once the calibration scripts were run, the probed points which give rise to the articulating surfaces of the joint were mapped onto a graph. The shape of the condyles and 'shortest distance' points whereby the displacement output variables were calculated were then checked manually.

5.3.3 Knee Angle Calculations

Calculations of knee angles requires a well-defined Joint Coordinate System (JCS) to capture the primary planes of knee movement: flexion-extension, abduction-adduction, and internal-external rotation. Following Grood and Suntay's (1983) framework, the JCS is structured to provide a clinically relevant and consistent basis for reporting three-dimensional joint motions(176). The ISB (Wu et al., 2002) endorses this system by standardizing axis definitions for each joint to ensure clear and comparable measurement outcomes across studies (177).

In this study, knee angles were processed using Vicon Nexus software, which uses the following axis configuration in its outputs:

- X-axis: Flexion-extension (matches ISB convention).
- Y-axis: Abduction-adduction (differs from ISB, where abduction is typically assigned to the Z-axis).

- Z-axis: Internal-external rotation (differs from ISB, where this is typically measured along the Y-axis).

To implement this JCS, a 4-marker rigid cluster for each segment was used to define the orientation of each body part in 3D space. While this configuration differs from the ISB standards, it maintains the separation of primary movements into distinct planes. These axes define movements independently of the rotation sequence used in calculations. For this study, a ZXY rotation order was selected, meaning that internal-external rotation (Z-axis) was calculated first, followed by flexion-extension (X-axis) and abduction-adduction (Y-axis). This separation of rotation order from axis definitions helps minimise crosstalk between planes, isolating flexion-extension as the primary plane of knee movement.

Adhering to a consistent axis setup, even when different from ISB conventions, supports reproducibility of measurements and comparability in biomechanical studies. This is particularly important in conditions such as ACL injuries where rotational stability is critical to both diagnosis and treatment.

Changing the rotation order (e.g., to *yxz*) would yield different angle outputs due to the interdependence of rotations in 3D space, as highlighted by Grood and Suntay (1983) and Wu et al. (2002)(176, 177). Each axis influences the subsequent rotations, so altering the sequence can affect the calculated angles and thus the clinical interpretation of joint movements.

This setup supports precise, clinically meaningful measurements, especially for conditions like ACL injuries, where rotational stability is essential. Adhering to a standardized axis setup improves the reproducibility of these measurements and enables comparability in biomechanical research.

In summary, this axis configuration and rotation order support reliable, clinically relevant data capture for knee biomechanics by isolating movements in each plane. The use of a standardized JCS and specific axis alignment provides a robust basis for analysing knee joint kinematics accurately in both research and clinical settings.

5.3.4 VICON Outputs for Laxity Calculations

Vicon model outputs were produced once the custom MATLAB processing scripts were run. These are anterior displacement values relative to the medial, mid-point and lateral sides of the knee. The displacement model outputs that were produced and analysed were: DrawDynMed, DrawDynMid and DrawDynLat.

DrawDynMid was the quantifiable output used to compare across subjects when commenting on laxity in the AP plane [Figure 33]. DrawDynMed and DrawDynLat produce quantifiable outputs of rotational laxity, by looking at anterior displacement relative to the medial and lateral femoral condyle [Figure 32 and Figure 34]. Joint angles were calculated for the knee, hip and ankle, each of these have outputs in 3 planes of movement the X, Y and Z were investigated for each respective joint.

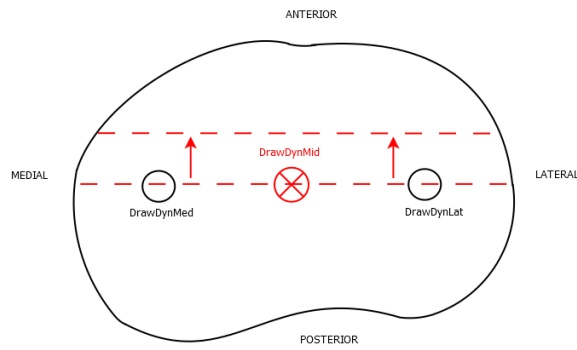


Figure 33: Diagram showing anterior tibial translation relative to the DrawDynMid point (central to the knee).

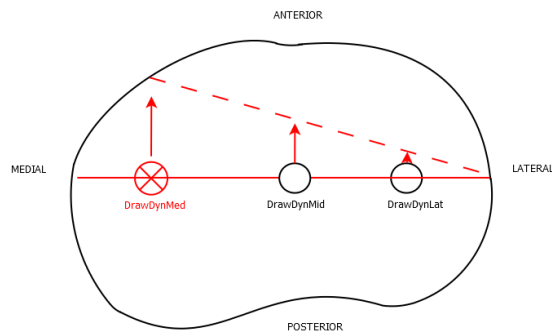


Figure 32: Diagram showing anterior tibial translation relative to the medial aspect of the knee, also demonstrating changes in Anteromedial Rotary Laxity.

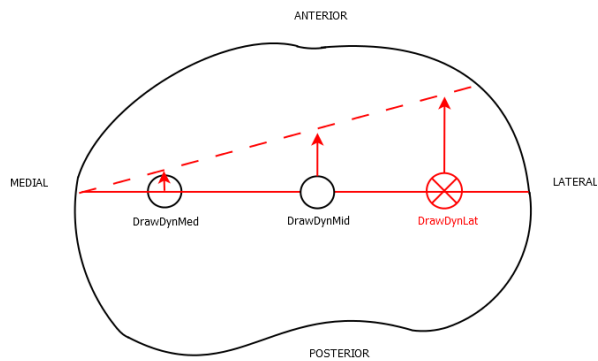


Figure 34: Diagram showing anterior tibial translation relative to the lateral aspect of the knee, also demonstrating changes in Anterior Lateral Rotary Laxity.

5.3.5 Quantifying Knee Laxity: Anterior Tibial Translation (ATT)

Anterior tibial translation (ATT) was calculated from the Vicon data using the midpoint of the knee mapped from the calibration probe, the process is explained in 5.2.9. ATT was initially recorded as an absolute value in millimetres for each knee. However, absolute values alone do not account for individual baseline variability in knee laxity. For instance, one person's healthy knee might translate 8mm, while another's injured knee could also translate 8mm, with their healthy knee translating only 4mm. In this case, the difference in translation between the injured and healthy knee is more clinically significant than the absolute value. Clinically, both knees are always tested, with the healthy knee serving as a control, and the difference in translation indicating potential structural changes.

For this reason, as well as the range of absolute translation (mm) for each leg, ratio values were calculated which were reported as a proportion relative to the patient's contralateral leg, acting as a measure of laxity asymmetry.

$$\text{Injured Participant} = \frac{\text{ATT of Injured Leg(mm)}}{\text{ATT of contralateral Healthy Leg(mm)}}$$

$$\text{Healthy Participant} = \frac{\text{ATT of left Healthy Leg (mm)}}{\text{ATT of right Healthy Leg (mm)}}$$

Two different ratio variations were calculated. The first was labelled as the 'RangeMeanMeanNorm', this represented the average displacement exerted over multiple reps as a proportion of that of the contralateral leg, it was calculated by averaging the amount of translation over all the repetitions of the given clinical test performed on one leg and repeating this process on the contralateral leg.

The other ratio calculated was called the 'RangeMaxMaxNorm', this represented the maximum amount of displacement induced over all the repetitions as a proportion of that of the contralateral leg. It was calculated by obtaining the maximal displacement value of the leg in question and dividing it by the maximal displacement value of the contralateral leg.

When performing laxity tests to the acutely injured patient, an involuntary muscle contraction to muscle groups surrounding the knee can often occur also known as ‘muscle guarding’, this restricts the amount of translation the clinician can induce. The RangeMeanMeanNorm accounts for such variability by averaging out the amount of translation over multiple reps, and as such the mean value may be a more robust metric when dealing with lots of data points as it accounts for outliers. In contrast, the RangeMaxMaxNorm provides the representation of the largest displacement value. In current clinical practice it is the maximal amount of translation that is indicative of the injury.

Three clinical tests were performed to test for anterior tibial translation; the anterior drawer tests, the Lachman test, and the anterior drawer whilst sat on the edge of the bed test.

In subsequent data analysis an assessment for data normality included graphical analysis using histograms and Q-Q plots, as well as a value >0.05 in the Shapiro-wilks test. For the range of the anterior drawer test the healthy control subjects’ data was not normally distributed, for this reason non-parametric tests were used to assess for statistical differences between the injured and healthy cohort. For the Ratio data for this test, the data of both cohorts followed a normal distribution so independent sample T-tests were used.

5.3.6 Quantifying Anteromedial Rotary Laxity (AMRL)

The Feagin-Thomas test was performed as discussed in methods section 5.2.14, the aim of this test is to strain the knee to examine the amount of anteromedial rotary laxity (AMRL) in the knee, testing the integrity of the deep MCL which is commonly injured alongside the ACL.

This test is gaining popularity in the clinical world as a means to assess for AMRL, however there has not been any scientific evaluation of this clinical test to date.

As discussed in 4.3 when the knee is uninjured the COR occurs in the midpoint of the knee [Figure 35]. When the ACL and the MCL are injured then the COR moves laterally, giving rise to medial compartment joint laxity [Figure 36]. AMRL was therefore calculated by looking at the change in the DrawDynMed output as displayed in Figure 32.

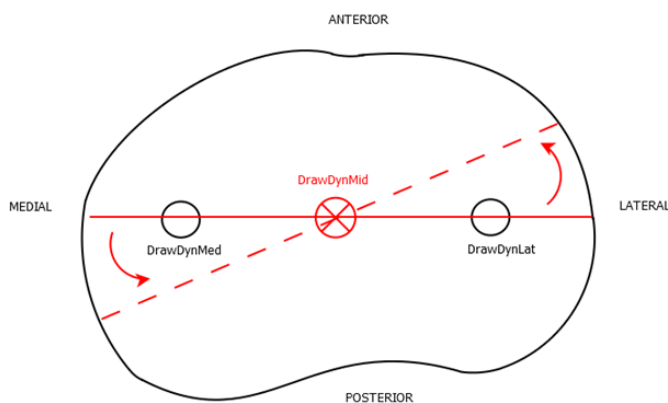


Figure 35: Centre of rotation example in the healthy knee

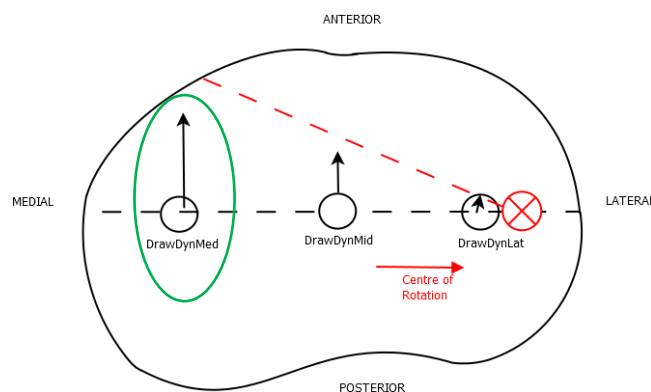


Figure 36: Centre of Rotation shift in the MCL Injured participant

To ensure correct handling, the DrawDynMed output was plotted time normalised to the change in internal external rotation angle. The assessor is inducing both external rotation as well as anterior displacement when performing this test. The DrawDynMed output was plotted for each rep of the test for the respective participant, each plot was manually checked. The trials were evented by defining each repetition as the trough in the Z axis (the point of maximal internal rotation).

For the tests which were deemed as having 'correct handling' the DrawDynMed output should positively correlate with an increase in external tibial rotation, the highest point in the DrawDynMed output would be approximately 40-70% through the trial duration. For tests deemed as having 'incorrect handling' the DrawDynMed output will not increase with an increase in external rotation and/or the peak in in the output will be way out of the 40-70% timestamp. Tests with 'incorrect handling were removed from data analysis.

6 Quantifying Knee Laxity with Motion Capture

6.1 Background

The previous chapter outlined the methodology used to capture and calculate knee laxity with precision. This chapter presents the results of the cohort study that evaluated knee laxity using optical motion capture (OMC) in both ACL-injured and healthy control subjects during clinical assessment techniques.

By quantifying knee laxity with sophisticated OMC systems, this study was able to capture the movements in knee biomechanics between injured and healthy cohorts. This approach also enabled a detailed comparison of different clinical tests, helping to elucidate their relative benefits in assessing knee laxity. Beyond defining laxity as a ground truth in clinical settings, the research conducted complex analyses to explore the impact of other injury-related factors on laxity, which could further inform future assessments.

Additionally, collecting OMC data during clinical assessments for both cohorts allowed for precise timestamping and normalisation of data from electromyography (EMG) and inertial measurement unit (IMU) sensors, enhancing the accuracy of the evaluation. The subsequent stages of this project, as discussed in Chapter 7, involve assessing the effects of muscle guarding, and Chapter 9 examines whether a wearable system can effectively capture joint laxity.

Research Question:

Can we differentiate between ACL injured and healthy participants by evaluating the amount of laxity with optical motion capture across multiple clinical tests?

Sub-Questions:

- Which is the best clinical test to assess for anterior knee laxity?
- Does the extent of additional knee trauma (ligamentous or meniscus injury) affect the amount of anterior laxity in the ACL injured cohort?
- Do subjective history criteria affect the amount of laxity in the ACL injured population?
- What is the agreement between the Lachmeter readings and VICON readings of knee laxity?
- What is the Diagnostic Ability of the Lachmeter?

- Is the Feagin-Thomas test sensitive in identifying Anteromedial Rotary Laxity?

Clinical Test Abbreviations:

AD- Anterior drawer test

LM- Lachman test

ADSOEOB- Anterior drawer sat on the edge of the bed test

6.2 Results

6.2.1 Anterior Knee Laxity: Comparing the Different Clinical Tests

When analysing the ATT (mm), the cohort of participant's limbs were divided into 2 groups, the ACL injured legs (n=25) and the uninjured control legs (n=75) (this group was comprised of the healthy control subject legs (n=52) and the uninjured limb of the ACL subjects (n=23)).

When analysing the ratios of translation, the data was handled differently, as previously stated [section 5.3.5], ratios were reported as a singular value for the respective leg, for this reason the injured leg of the injured cohort (n=23) was compared against the left leg of the healthy control subject (n=26). There were fewer injured legs involved in the ratio analysis (anterior laxity asymmetry) than that of the range (ATT mm), this is because one of the participants had bilateral ACL tears, for this reason said participant was removed from the ratio data.

As can be seen in Table 20, on average, the anterior drawer seated on edge of the bed (ADSOEOB) test yielded the greatest total amount of ATT (mm), followed by the Lachman test (LM), followed by the standard anterior drawer test (AD). However, when evaluating the side-to-side difference (mm) between healthy and injured legs, there was a difference of 2.68mm (+/-0.538), 1.40mm (+/-0.517), and a 1.61mm (+/- 0.318) difference in the ADSOEOB, LM, and AD test respectively. There was greater cohort variation in the LM and ADSOEOB than the AD tests in both the injured and healthy cohort, this is reflected in the standard deviations [Table 20].

Table 20: Overview of Anterior Tibial Translation (ATT) Measurements in Millimetres (mm) for ACL Injured Participants (n=25) and Healthy Uninjured Legs which were the Healthy Control Subjects legs (n=52) and the Uninjured Limbs of ACL Injured Participant (n=23). This table encompasses data from 26 healthy control subjects, 23 uninjured leg of the ACL injured subjects and 25 ACL injured legs.

Test and Cohort	Number of Knees	Number of reps	Min	Max	Mean	SD
Injured Cohort AD TEST	25	297	1.12	15.3	6.66	0.23
Healthy Cohort AD TEST	75	771	0.70	13.0	5.05	0.22
Injured Cohort LM TEST	25	410	2.70	23.4	9.80	0.38
Healthy Cohort LM TEST	75	958	1.61	20.4	8.40	0.35
Injured Cohort ADSOEOB TEST	25	193	6.40	26.3	13.60	0.40
Healthy Cohort ADSOEOB TEST	75	408	3.45	26.0	10.92	0.36

Graphical plots such as histograms and Q-Q Plots, as well as the Shapiro-Wilks normality distribution tests were checked for each clinical test, for the injured and healthy population groups. For the range (mm) outputs, data was not normally distributed for both the injured and healthy population groups, therefore nonparametric tests were run individually for each clinical laxity test, to evaluate the differences of ATT (mm) between in ACL injured and uninjured legs for each respective test.

There appeared statistically significant differences ($p < 0.001$) between the amount of anterior displacement induced between the cohorts. The effect sizes of ATT across the three clinical tests also represent the variability in the magnitude of the differences between population groups. The AD test provided a moderate effect size (0.506) demonstrating it may be more effective for detecting differences in ATT (mm). The ADSOEOB had a smaller effect size of 0.392 showing a lesser ability to differentiate between the two groups. In contrast, the LM test, with the lowest effect size (0.227), which demonstrates limited diagnostic utility in distinguishing between injured and non-injured states [Appendix D: Laxity tables].

For all clinical tests, both the MaxMaxNorm and MeanMeanNorm show that within the healthy control subjects the ratio output varied between 0.98-1.05. A ratio of 1 means that the laxity of the left leg is exactly that of the right leg, the highest value is 1.05 therefore the healthy control subjects in this instance showed no more than a 5% side to side difference in anterior laxity asymmetry.

The AD test produced the greatest relative increase in anterior laxity asymmetry for injured participants when compared to the ADSOEOB and LM test [Table 21]. Thus, showing that although the AD test may not elicit the most translation as an absolute distance of translation (mm), it shows the greatest increase in anterior laxity asymmetry measured the leg is measured relative to the contralateral leg and therefore appears more sensitive in identifying ACL injury.

Table 21: Comparison of Anterior Tibial Translation (ATT) Ratios Between ACL-Injured and Healthy Control Subjects. This table presents ATT ratios, defined as the ATT of one leg relative to its contralateral counterpart. The sample includes 23 ACL-injured leg.

Descriptives	N	Min	Max	Mean	Mean Cohort translation Ratio Increase(%)	SD
AD TEST Injured Cohort MaxMaxNorm	23	0.55	1.74	1.42	42%	.437
AD TEST Healthy Control MaxMaxNorm	26	0.32	1.74	1.00		0.295
AD TEST Injured Cohort MeanMeanNorm	23	0.42	2.93	1.52	54%	0.585
AD TEST Healthy Control MeanMeanNorm	26	0.46	1.49	0.98		0.277
LM TEST Injured Cohort MaxMaxNorm	23	0.87	1.89	1.26	25%	0.326
LM TEST Healthy Control MaxMaxNorm	26	0.52	2.02	1.01		0.337
LM TEST Injured Cohort MeanMeanNorm	23	0.70	1.82	1.24	24%	0.302
LM TEST Healthy Control MeanMeanNorm	26	0.51	1.86	1.00		0.343
ADSOEOB TEST Injured Cohort MaxMaxNorm	22	0.65	2.07	1.29	26%	0.354
ADSOEOB TEST Healthy Control MaxMaxNorm	19	0.59	1.84	1.03		0.351
ADSOEOB TEST Injured Cohort MeanMeanNorm	22	0.60	2.01	1.31	25%	0.354
ADSOEOB TEST Healthy Control MeanMeanNorm	19	0.55	1.8	1.06		0.367

MaxMaxNorm = The ratio of ATT using the maximal displacement induced over multiple reps on one leg and the maximal displacement induced over multiple reps of the contralateral leg.

MeanMeanNorm= The ratio of ATT using the mean displacement induced over multiple reps on one leg and the mean displacement induced over multiple reps of the contralateral leg.

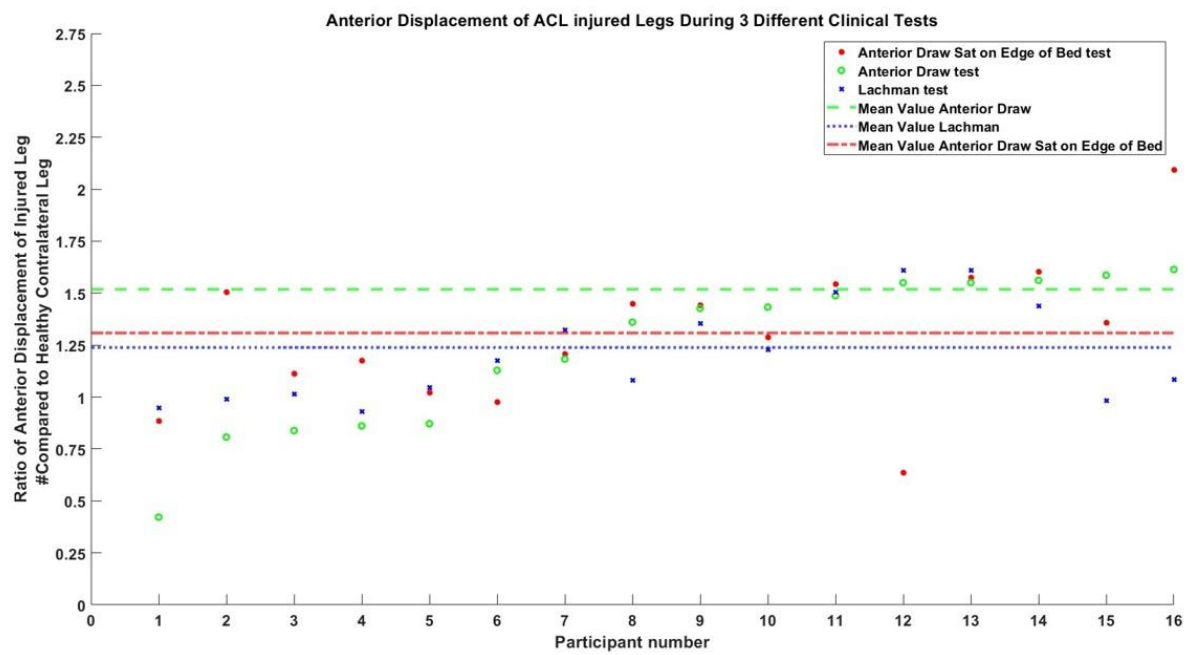
The normality distribution was also evaluated for ratio output laxity data. Both visual graphical data as well as Shapiro-wilks test revealed normal distributions for both the injured and healthy cohort. Therefore, parametric tests were run to evaluate the differences between cohorts. These anterior laxity asymmetry (ratio) findings indicate that all three tests can differentiate between the ACL injured and healthy control subjects with respect to anterior tibial translation [Appendix D: Laxity tables]. The AD test, particularly in the RangeMeanMeanNorm measure, showed the most substantial differences, with significant t-test results ($p > 0.001$) and moderate effect sizes [Table 22], suggesting higher sensitivity in detecting differences. The LM Test, while still showing significant differences ($p = 0.014$ and $p = 0.012$) respectively for the RangeMaxMaxNorm and the RangeMeanMeanNorm, had smaller effect sizes [Table 22], indicating a more modest differentiation capability. Similarly, the ADSOEOb Test also demonstrated significant differences ($p > 0.003$) but with lower effect sizes [Table 22], akin to the LM Test. These results collectively highlight the effectiveness of each test in differentiating anterior tibial translation in the context of ACL injuries, with the AD Test appearing to be the most sensitive. [Appendix D: Laxity tables]

Table 22: Effect sizes for all Clinical Tests

Clinical Test	Ratio Type	Cohen's d
AD test	RangeMaxMaxNorm	0.384
	RangeMeanMeanNorm	0.448
LM test	RangeMaxMaxNorm	0.332
	RangeMeanMeanNorm	0.324
ADSOEOb	RangeMaxMaxNorm	0.353
	RangeMeanMeanNorm	0.360

Although the AD test yielded the most relative asymmetry anterior knee laxity on average, there were multiple instances where the LM test or the ADSOEOb test superseded it for certain participants. Figure 37 displays a scatter plot for 16 participants who all had all 3 clinical tests performed, therefore showing that one test is not consistently higher than the others.

Figure 37: Scatter Plot of Showing Difference in Laxity Ratios Between the Three Clinical Tests Across 16 ACL Injured Participants



6.2.2 Anterior Laxity in Concomitant Ligament and Meniscal Injuries

For this analysis, only ACL injured knees were included. The ACL injured cohort was divided into isolated ACL injured participants (iACL)(n=11), ACL with one additional ligament injury (n=6) and ACL with 2 additional ligament injuries (n=8). Additional ligamentous injuries were counted as the following: Deep MCL, Superficial MCL, LCL and PCL. The superficial and deep MCL were treated separately due to their different insertion point on the tibia. A breakdown of additional ligamentous injuries can be found in Figure 38. Subsequent analysis was by number of additional injuries rather than a breakdown of exact injuries, this was due to the small sample size.

Further categorisation was performed in relation to the presence of meniscus injuries, where those without meniscus injuries were in one group (n=9), those with one meniscus injury were in another (n=10) and those with two meniscal injuries were in a third group (n=6) (Figure 39).

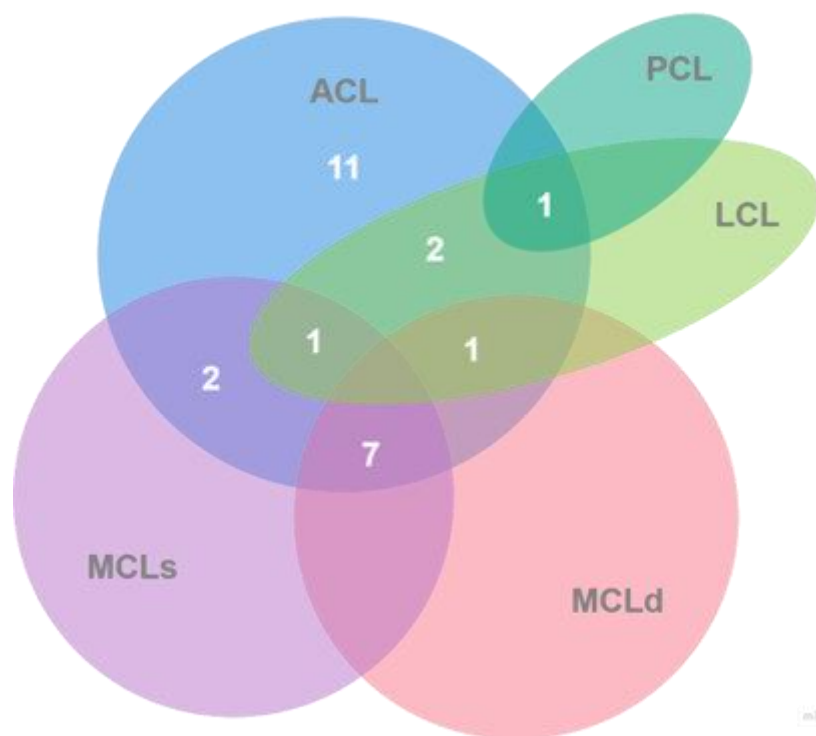


Figure 38: Concomitant Ligament Injury Frequency Venn-Diagram

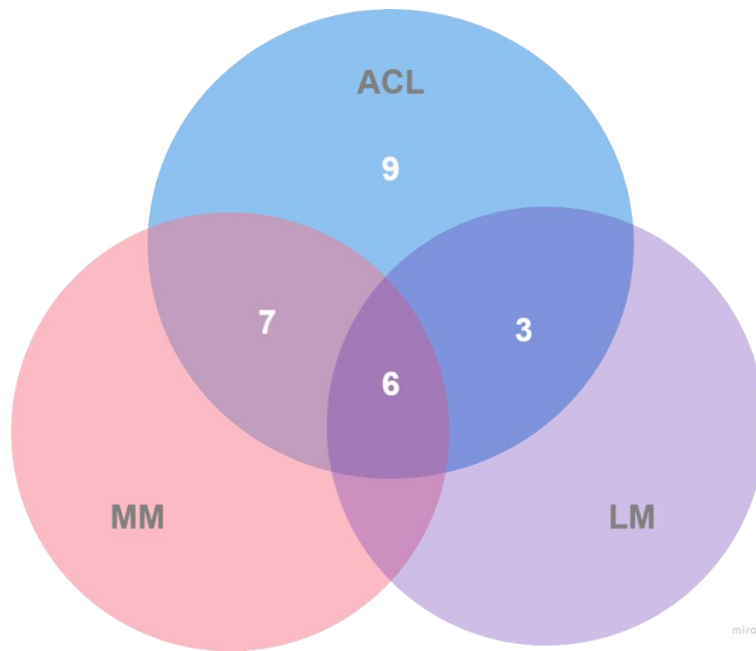


Figure 39: Concomitant Meniscus Injury Frequency Venn-Diagram

To investigate if the amount of ATT was affected by additional sustained injuries, ANOVA tests were run separately for patients with additional ligamentous and those with meniscus injuries. Data for all 3 clinical tests were included and this analysis was repeated for the range and the ratio outputs. Data was grouped as per Table 23 and Table 24.

Table 23: Groupings for Meniscus Injuries

Group No.	Injury Type	Number of Participants (n)
1	ACL No Meniscus	9
2	ACL+1 Meniscus	10
3	ACL+2 Meniscus	6

Table 24: Groupings for Additional Ligament Injuries

Group No.	Injury Type	Number of Participants (n)
1	ACL No Other ligaments	11
4	ACL+1 Other Ligament	4
3	ACL+2 Other Ligament	10

As can be seen in Figure 41 and Figure 40, the ATT (mm) data were not normally distributed, transformations were attempted however these were not successful. Although the data did not follow normality, nonparametric test equivalents were not appropriate, and the large sample size (n=900 repetitions) negated the importance of a clear normal distribution. As a result, these findings should be interpreted with caution.

Figure 41: Histogram of ACL Injured ATT (mm) Distribution in Millimetres Across All Clinical Tests. This figure illustrates the normality of data distribution for ACL-

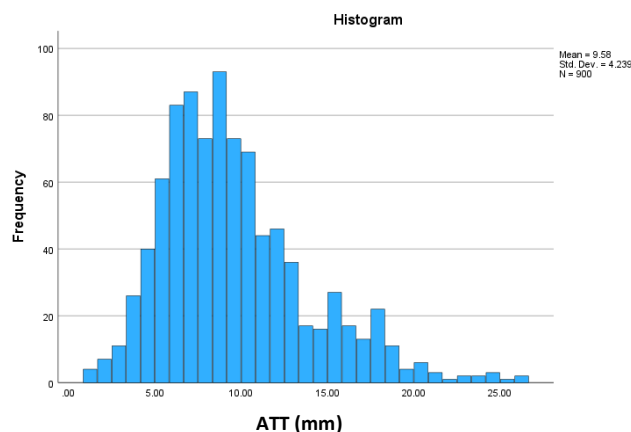
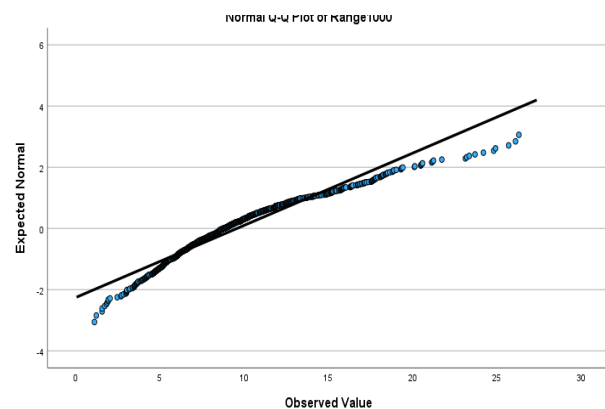


Figure 40: Q-Q Plot Analysis of ATT (mm) for ACL-Injured Participants Across All Clinical Tests. This figure visually assesses the normality of distribution through quantile-quantile comparison.



When looking at the relationship between anterior laxity and concomitant ligamentous injury, there was no relationship of increasing mean ATT (mm) [Table 25] or mean anterior laxity asymmetry (ratio) [Table 26] with increasing concomitant knee injury groupings. In addition to assessing if there was an increasing trend with the mean value of ATT and an increase in additional concomitant injury (mm and ratio), ANOVA tests were completed to evaluate if there were any significant differences within the sub-groups of the ACL injured cohort subjects [Appendix D: Laxity tables], however these suggested that there was no relationship between ATT and increased severity of concomitant knee ligament injury.

Table 25: Descriptive Statistics of ATT (mm) for Participants with Additional Ligamentous Injuries.

Group	N (Number of participants in each group)	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	11	9.87	4.66	0.228	9.42	10.3	1.12	26.3
2	6	8.82	3.22	0.256	8.32	9.33	2.85	17.6
3	8	9.57	4.06	0.226	9.13	10.0	1.73	26.1
Total	25	9.58	4.24	0.141	9.30	9.86	1.12	26.3

Group 1: ACL Without Meniscus; Group 2: ACL +1 Meniscus; Group 3: ACL+2 Meniscus

Table 26: Descriptive Statistics of ATT Ratio as proportion of contralateral leg Among ACL-Injured Cohorts: No Additional Ligament Injuries, One Additional Ligament Involved, and Two Additional Ligaments Involved

Descriptives									
Ratio Type	Grouping	N (Number of participants in each group)	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
RangeMaxMaxNorm	1	10	1.31	0.40	0.07	1.16	1.46	0.55	2.07
	2	6	1.47	0.49	0.14	1.15	1.78	0.94	2.68
	3	7	1.26	0.31	0.06	1.14	1.38	0.65	1.90
	Total	23	1.32	0.39	0.05	1.22	1.41	0.55	2.68
RangeMeanMeanNorm	1	10	1.40	0.47	0.09	1.22	1.58	0.42	2.54
	2	6	1.44	0.57	0.16	1.07	1.80	0.87	2.94
	3	7	1.28	0.34	0.07	1.14	1.41	0.60	2.00
	Total	23	1.36	0.44	0.05	1.25	1.47	0.42	2.94

Group 1: ACL Isolated; Group 2: ACL +1 Additional Ligament; Group 3: ACL+2 Additional Ligament

****N values of groupings are different to ATT (mm) – due to 1 participant having B/L injuries they were excluded from Ratio Calculations****

ATT (mm) and ratio values of ATT asymmetry between legs were also compared for groups with increasing concomitant meniscus injury. Table 27 shows an incremental increase in the mean value of ATT (mm) with increasing meniscal injury, this would suggest that an increase in meniscus injury severity is associated with an increase in absolute anterior tibial translation in the injured leg. On completing post-hoc tests [Table 28] the significant changes in these results lay between groups 1 and 3, and groups 2 and 3. However, this is not reflected in the anterior laxity asymmetry (ratio) values [Table 29], thus showing that the differences between

the injured and healthy leg of the ACL injured individual does not show the same increase in anterior laxity when there is increased meniscus damage. This suggests that the increase in ATT (mm) may be due to other factors beyond the extent of anatomical damage to the joint due to the disagreement when the same relationship was investigated with ratio values. Overall, there is insufficient evidence to suggest increased concomitant injury additional to ACL damage is associated with increased anterior knee laxity.

Table 27: Descriptive Statistics of ATT (mm) Among ACL-Injured Cohorts: No Additional Meniscus Injuries, One Meniscus Involved, and Two Meniscus Involved.

Descriptives								
Grouping	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1	9	8.82	3.97	0.23	8.35	9.28	1.73	20.55
2	10	9.29	4.14	0.21	8.87	9.71	1.12	26.11
3	6	10.92	4.22	0.26	10.41	11.43	4.15	26.31

Group 1: ACL Without Meniscus; Group 2: ACL +1 Meniscus; Group 3: ACL+2 Meniscus

Table 28: Post-Hoc Tests for ATT Range (mm) Between Meniscus Injury Groupings

Multiple Comparisons						
Dependent Variable: Range1000						
Bonferroni						
(I) MenGroupingVariable	(J) MenGroupingVariable	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	-0.477	0.323	0.419	-1.25	0.297
	3	-2.10	0.350	<.001	-2.94	-1.26
2	1	0.477	0.323	0.419	-0.297	1.25
	3	-1.63	0.330	<.001	-2.42	-0.834
3	1	2.10	0.350	<.001	1.26	2.94
	2	1.63	0.330	<.001	0.834	2.42
*. The mean difference is significant at the 0.05 level.						

Group 1: ACL Without Meniscus; Group 2: ACL +1 Meniscus; Group 3: ACL+2 Meniscus

Table 29: Descriptive Statistics of ATT Ratio as proportion of contralateral leg Among ACL-Injured Cohorts: No Additional Meniscus Injuries, One Meniscus Involved, and Two Meniscus Involved.

Descriptives									
		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
RangeMaxMaxNorm	1	8	1.43	0.43	0.09	1.23	1.62	0.91	2.68
	2	10	1.21	0.38	0.07	1.07	1.35	0.55	2.07
	3	5	1.39	0.27	0.07	1.24	1.54	0.86	1.97
	Total	23	1.32	0.39	0.05	1.22	1.41	0.55	2.68
RangeMeanMeanNorm	1	8	1.46	0.54	0.12	1.22	1.71	0.84	2.94
	2	10	1.24	0.41	0.07	1.09	1.39	0.42	2.09
	3	5	1.46	0.3	0.08	1.3	1.62	0.98	2.27
	Total	23	1.36	0.44	0.05	1.25	1.47	0.42	2.94

Group 1: ACL Without Meniscus; Group 2: ACL +1 Meniscus; Group 3: ACL+2 Meniscus

****N values of groupings are different to ATT (mm) – due to 1 participant having B/L injuries they were excluded from Ratio Calculations****

6.2.3 Subjective History Criteria and Anterior Knee Laxity

The next aim was to investigate the relationship between subjective history indicators of ACL injuries and anterior laxity in the ACL injured cohort. The LIMP index is an acronym formed of 4 subjective history factors; Leg giving way at time of injury, Inability to continue activity, Marked effusion and Pop at time of injury. Data was analysed by grouping the ACL injured participants into the number of LIMP index factors injured participants reported [Table 30].

Table 30: Detailed Breakdown of the LIMP Index: Factor Count, Participant Distribution by Number of Factors, and Clinical Test Repetition Frequency. This table systematically categorises the LIMP index by the number of factors included, presents the participant count for each factor level, and outlines the repetition rates for each associated clinical evaluation.

LIMP Factors	Number of participants	Number of repetitions involved in analysis (Data Points)	Average number of reps per participant
0	1	19	19
1	1	42	42
2	3	114	38
3	4	136	34
4	16	589	37

Data distribution was normal for each of the LIMP factors, therefore an ANOVA was used. Similar to findings of concomitant injuries, although the ANOVA results for the ATT (mm) showed significant differences between the patient groups ($P < 0.01$) this was not influenced by the number of LIMP factors reported [Table 31 and Table 32]. The ANOVA results for the anterior laxity asymmetry (ratio) data did not reflect the same differences of increased ATT with increased LIMP index scores between groups ($p = 0.407$ and $p = 0.554$). This means that despite the changes in ATT (mm) between the groups this is not due higher LIMP index scores.

Table 31: Summary Statistics of Anterior Tibial Translation (mm) in Millimetres for Participants Categorised by LIMP Factor Levels. This table provides mean values, standard deviations, and other descriptive metrics for ATT (mm), organised by the varying number of LIMP index factors among participants.

Descriptives								
LIMP Factors	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
0	19	9.6190	1.59058	.36490	8.8524	10.3856	6.77	12.66
1	42	6.5172	2.45891	.37942	5.7509	7.2834	2.70	10.52
2	114	8.9912	3.56912	.33428	8.3289	9.6534	2.85	18.14
3	136	8.9965	3.88769	.33337	8.3372	9.6558	1.73	20.55
4	589	10.0462	4.47432	.18436	9.6841	10.4083	1.12	26.31
Total	900	9.5802	4.23879	.14129	9.3029	9.8575	1.12	26.31

Table 32: Descriptive Statistics of ATT Ratio Across LIMP Index Groupings.

Descriptives									
Ratio	LIMP Factors	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
RangeMaxMaxNorm	0	3	0.96	0.12	0.07	0.66	1.26	0.88	1.1
	1	3	1.47	0.53	0.31	0.15	2.78	0.87	1.9
	2	9	1.24	0.35	0.12	0.97	1.51	0.86	1.97
	3	11	1.27	0.3	0.09	1.07	1.47	0.97	1.87
	4	42	1.36	0.41	0.06	1.23	1.49	0.55	2.68
	Total	68	1.32	0.39	0.05	1.22	1.41	0.55	2.68
RangeMeanMeanNorm	0	3	0.99	0.16	0.1	0.58	1.4	0.86	1.18
	1	3	1.48	0.69	0.4	-0.24	3.19	0.7	2
	2	9	0.96	0.12	0.07	0.66	1.26	0.88	1.1
	3	11	1.47	0.53	0.31	0.15	2.78	0.87	1.9
	4	42	1.24	0.35	0.12	0.97	1.51	0.86	1.97
	Total	68	1.27	0.3	0.09	1.07	1.47	0.97	1.87

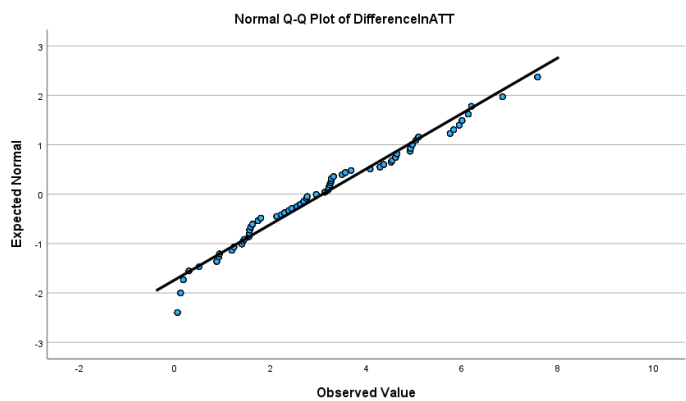
6.2.4 Arthrometry Accuracy and Agreement with VICON

The agreement between the Lachmeter results and OMC readings of ATT (mm) were investigated using Intraclass Correlation Coefficients (ICC) and Bland-Altman plots. Normalcy of data is usually required when using these statistical tests, although normality is not reflected in the Shapiro-Wilk test [Table 33], the Q-Q plot reflects a normal data set graphically [Figure 42], therefore normality was assumed, however, these results should be interpreted with caution.

Table 33: Normality Assessment of ATT Difference Measures Across Participants.

Tests of Normality						
	Kolmogorov-Smirnov			Shapiro-Wilk		
	Statistic	Df	Sig.	Statistic	Df	Sig.
DifferenceInATT	0.096	901	<0.001	0.969	901	<0.001

Figure 42: Q-Q Plot Visualizing the Distribution of ATT Differences.



An ICC of 0.507 indicates moderate reliability between the two methods of measuring anterior tibial translation [Table 34], suggesting that while there is some correlation, the measurements are not highly consistent with each other. This moderate level of agreement is supported by the Bland-Altman plot, which shows a mean difference of 3.088 units [Figure 43], indicating a systematic bias where OMC is consistently reports higher values than the Lachmeter values. Furthermore, the limits of agreement, ranging from -0.403 to 6.58, are wide. The poor agreement between the two methods demonstrates that Lachmeter results are not consistent with those of the OMC. This means that for individual measurements, the two methods differ by a substantial amount, which could have significant implications for clinical decision-making. The Bland-Altman plots, however, do not indicate a proportional

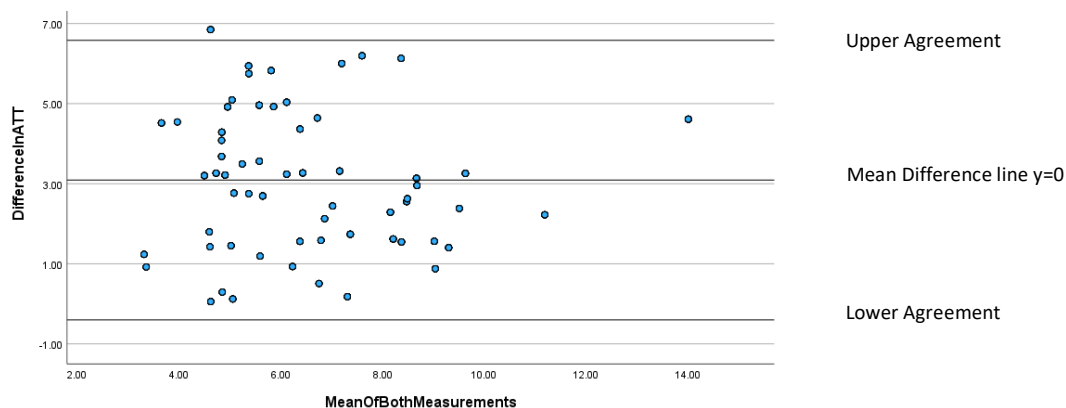
bias, as the differences do not show a trend of increasing or decreasing with the magnitude of the measurements.

Table 34: Intraclass Correlation Coefficient (ICC) Analysis for Agreement on Anterior Tibial Translation Measurements Between Lachmeter and Optical Motion Capture System.

Intraclass Correlation Coefficient							
	Intraclass Correlation ^b	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.507 ^a	.475	.539	3.059	2082	2082	<.001
Average Measures	.673 ^c	.644	.700	3.059	2082	2082	<.001
Two-way mixed effects model where people effects are random and measures effects are fixed.							
a. The estimator is the same, whether the interaction effect is present or not.							
b. Type C intraclass correlation coefficients using a consistency definition. The between-measure variance is excluded from the denominator variance.							
c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.							

The mean difference (bias) is 3.088 units, with limits of agreement ranging from -0.403 to 6.58 units. The plot shows moderate agreement with a systematic bias, indicating that the Optical Motion Capture System tends to measure higher than the Lachmeter readings.

Figure 43: Bland-Altman Plot for Comparing Lachmeter and Optical Motion Capture System in Measuring Anterior Tibial Translation.



The data collected from the Lachmeter readings for the healthy control subjects and ACL injured participants were recorded. Descriptives outlining the minimum, maximum and mean value for the recorded Lachmeter values can be found below [Table 35]. The data for both cohorts were non-normally distributed [Appendix D: Laxity tables], Mann-Whitney U test revealed significant differences for Lachmeter values [Table 36] between the ACL injured and the healthy control cohort.

Table 35: Descriptive statistics of Lachmeter Readings for the ACL Injured and Healthy Control Subjects

Test and Cohort	Number of Knees	Min	Max	Mean	SD
Injured Cohort Lachmeter	19	1.40	12.3	7.21	2.97
Healthy Cohort Lachmeter	47	1.20	9.80	4.12	1.71

Table 36: Comparative Analysis of Anterior Tibial Translation (ATT) from the Lachmeter Between the ACL Injured Participants and Healthy Control Subjects Using Non-Parametric Tests

Test Statistics ^a	
	LachUniqueValue
Mann-Whitney U	155.000
Wilcoxon W	1058.000
Z	-3.801
Asymp. Sig. (2-tailed)	<.001

Diagnostic accuracy and subsequent performance characteristics were calculated by using a threshold of 3mm or more side to side (STS) difference value to indicate an injured ACL group. This reported STS value is the difference in ATT between the two legs, a value of 3mm is reported in the literature as being indicative of ACL pathology when measuring for AP laxity with a Lachmeter or KT1000 (174, 178-180).

Lachmeter values were recorded as a side-to-side difference for each participant [Table 37]. Confirmed ACL injured participants and healthy control subjects were then marked as being a true positive, false positive, true negative, and false negative accordingly [Table 38], as per section 2.7. Relative diagnostic performance characteristic values were calculated [Table 39]. A Positive Predictive Value (PPV) of 81.8% shows that when the Lachmeter result is positive (indicating an ACL tear), there is an 81.8% chance that the individual has an ACL tear. A Negative Predictive Value (NPV) indicates that when the Lachmeter result is negative (indicating no ACL tear), there is a 61.9% chance that the individual does not have an ACL tear. A test sensitivity of 52.9%: demonstrates that the test correctly identifies 52.9% of individuals with ACL tears (true positive rate). A specificity of 86.7% reveals that the test correctly identifies 86.7% of individuals without ACL tears (true negative rate). Overall, the test correctly classifies 68.7% of all cases (both ACL tears and no ACL tears).

Table 37: Frequency Tables for Lachmeter (Side to Side Differences) Readings

Participants	n
--------------	---

Total	32
ACL injured	17
Healthy Controls	15

Table 38: Frequency Tables for the Positive and Negative Diagnosis based off a 3mm STS Difference in Lachmeter Readings

	n
True Positives (TP)	9
False Positives (FP)	2
True Negatives (TN)	13
False Negatives (FN)	8

Table 39: Diagnostic Performance Characteristics (DPC) Based off of a 3mm STS difference in Lachmeter Readings

DPC	%
Positive Predictive Value	81.8
Negative Predictive Value	61.9
Sensitivity	52.9
Specificity	86.7
Diagnostic Accuracy	68.7

Diagnostic accuracy and performance characteristics for the VICON readings during the Lachman test were calculated using a threshold of 3mm side-to-side (STS) difference, which is consistent with indicators for ACL pathology in measuring anterior-posterior (AP) laxity. The study included a total of 49 participants, with 23 confirmed ACL-injured individuals and 26 healthy controls [Table 40]. Diagnostic outcomes were classified into true positives, false positives, true negatives, and false negatives based on this 3mm threshold [Table 41]. The VICON Lachman test data yielded a Positive Predictive Value (PPV) of 90.9%, indicating that when the test result was positive (suggesting an ACL tear), there was a 90.9% likelihood that the participant indeed had an ACL tear. The Negative Predictive Value (NPV) was 65.8%, meaning that a negative test result had a 65.8% likelihood of correctly identifying participants without an ACL tear.

In terms of test sensitivity, the VICON readings accurately identified 43.5% of ACL-injured individuals, reflecting the true positive rate. Specificity was high at 96.2%, signifying that the test accurately classified 96.2% of participants without ACL injuries as healthy. Overall, the diagnostic accuracy for the VICON readings in the Lachman test was calculated to be 71.4%, demonstrating moderate effectiveness in distinguishing between ACL-injured and healthy participants [Table 42].

When comparing these results to the Lachmeter readings, the VICON demonstrated a higher specificity (96.2% vs. 86.7%) and a slightly improved diagnostic accuracy (71.4% vs. 68.7%), suggesting a marginal advantage in correctly identifying healthy individuals.

Table 40: Frequency Tables for VICON readings during the Lachman test.

Participants	n
Total	49
ACL injured	23
Healthy Controls	26

Table 41: Frequency Tables for the Positive and Negative Diagnosis based off a 3mm STS Difference in VICON Readings during the Lachman test.

Test Outcome	n
True Positives (TP)	10
False Positives (FP)	1
True Negatives (TN)	25
False Negatives (FN)	13

Table 42: Diagnostic Performance Characteristics (DPC) Diagnosis based off a 3mm STS Difference in VICON Readings during the Lachman test.

Diagnostic Performance Characteristics (DPCs)	%
Positive Predictive Value	90.9
Negative Predictive Value	65.8
Sensitivity	43.5

Specificity	96.2
Diagnostic Accuracy	71.4

The diagnostic ability of the lachmeter results were also assessed by completing a binomial regression to establish the threshold at which injury would be considered when measuring ATT as a STS difference.

When assessing overall model performance, the overall classification accuracy improved from 53.1% at baseline to 68.8% after including the Lachmeter readings, indicating the model's enhanced predictive capability with this variable [Table 43]. The Omnibus Tests of Model Coefficients revealed a chi-square value of 5.532 with a significance level (p-value) of 0.019 suggests that the model with the Lachmeter readings improves the diagnosis of ACL injuries. The Lachmeter reading variable (STSLach) has a Wald statistic of 4.489 with a p-value of 0.034, indicating it is a predictor of ACL injury status [Table 44]. The positive coefficient ($B = .491$) suggests that higher side-to-side Lachmeter readings are associated with a higher likelihood of ACL injury [Table 44]. The $\text{Exp}(B)$ value for STSLach is 1.634, implying that for every one-unit increase in the Lachmeter reading, the odds of being in the ACL injured group (versus the control group) increase by 63.4%. The Hosmer and Lemeshow test assess the goodness of fit, showing a chi-square value of 6.036 and a p-value of .643, indicates that the model's predictions are not significantly different from observed outcomes, suggesting a good fit. The predictive accuracy classification tables for observed and predicted group memberships show improvement in predictive accuracy for both groups after incorporating the Lachmeter readings into the model.

Table 43: Classification Table showing observed vs. predicted group membership based on Lachmeter readings, with percentages correct for each group and overall percentage accuracy.

Classification Table ^a					
	Observed		Predicted		
			LachGroupingVariable		Percentage Correct
			.00	1.00	
Step 1	LachGroupingVariable	.00	11	4	73.3
		1.00	6	11	64.7
	Overall Percentage				68.8
a. The cut value is .500					

Table 44: Variables in the Equation for the final model, detailing the coefficients (B), standard errors (S.E.), Wald statistics, degrees of freedom, significance levels (Sig.), and exponentiated coefficients (Exp(B)) for predictors of ACL injury.

Variables in the Equation							
		B	S.E.	Wald	df	Sig.	Exp(B)
Step 1 ^a	STSLach	.491	.232	4.489	1	.034	1.634
	Constant	-1.004	.627	2.562	1	.109	.366
a. Variable(s) entered on step 1: STSLach.							

A ROC (Receiver Operating Characteristic) curve was constructed [Figure 44] in addition to a binomial regression to assess the diagnostic test's ability to distinguish between two conditions (e.g., ACL injured vs. healthy controls) across a range of thresholds. It provides a comprehensive measure of test performance, illustrating the trade-off between sensitivity (true positive rate) and specificity (true negative rate) at various threshold settings. This enables the determination of an optimal cutoff value that maximises both sensitivity and specificity, offering critical insights beyond the predictive strength of individual predictors in a regression model.

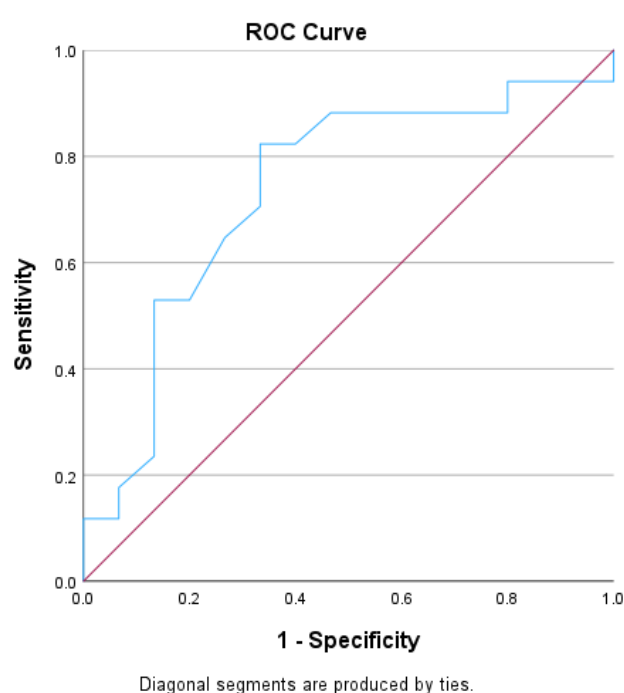


Figure 44: Receiver Operating Characteristic (ROC) Curve for Diagnosing ACL Injury with Lachmeter Readings, depicting sensitivity on the Y-axis and 1-specificity on the X-axis. The blue line represents the performance of the Lachmeter test across different thresholds, while the red diagonal line indicates the line of no discrimination, serving as a benchmark for random chance. The area between the blue curve and the red line illustrates the test's diagnostic ability above chance level.

Where positive outcome is an ACL injury, and a negative outcome indicates no injury, a higher score (STS difference) would indicate a more positive outcome. An area of 0.735 shows that the Lachmeter is a fair test [Table 45]. Values above or equal to 0.9 shows excellent diagnostic ability, ≥ 0.8 represents a good test, ≥ 0.7 represents a fair tests and values between 0.6-0.7 show poor diagnostic ability.

Table 45: Area Under the Curve (AUC) Analysis for Lachmeter Readings in Diagnosing ACL Injury, indicating the AUC value (.735), standard error, significance level ($p = .023$), and the confidence interval (CI) range (.553 to .918).

Area Under the Curve				
Test Result Variable(s): STSLach				
Area	Std. Error ^a	Asymptotic Sig. ^b	Asymptotic 95% Confidence Interval	
			Lower Bound	Upper Bound
.735	.093	.023	.553	.918
The test result variable(s): STSLach has at least one tie between the positive actual state group and the negative actual state group. Statistics may be biased.				
a. Under the nonparametric assumption				
b. Null hypothesis: true area = 0.5				

The values in the table ‘coordinates of the curve’ have a sensitivity column, where the values are the % of positive outcomes that would be correctly classified, the values in the 1-specificity column are the number of false positive outcomes [Table 46]. The closest reported value to a STS difference of 3mm would be the row of the value of 2.90 (highlighted), if a cut off value of 3mm was used to diagnose patients with ACL injuries, 52.9% of participants with an ACL tear would be correctly classified and 13.3% of participants would be incorrectly identified as being injured when they were in fact healthy. This would mean 47.1% of participants with an ACL injury would not be identified. By reducing the STS difference threshold, the analysis suggests you would increase the number of ACL injuries that are identified but you would also in turn increase the number of false positives. By increasing the threshold, the opposite effect would then occur.

Table 46: Coordinates of the ROC Curve for Lachmeter Readings, detailing sensitivity and 1-specificity values at various cutoff points

Coordinates of the Curve		
Test Result Variable(s): STSLach		
Positive if Greater Than or Equal To ^a	Sensitivity	1 - Specificity
-.8000	1.000	1.000
.2500	.941	1.000
.3500	.941	.800
.4500	.882	.800
.6000	.882	.733
.7500	.882	.667
.8500	.882	.533
1.0000	.882	.467
1.2000	.824	.400
1.3500	.824	.333
1.4500	.765	.333
1.6500	.706	.333
2.1000	.647	.267
2.5500	.529	.200

2.9000	.529	.133
3.4500	.471	.133
3.9000	.412	.133
4.0500	.353	.133
4.2500	.294	.133
4.6000	.235	.133
5.0500	.176	.067
5.4000	.118	.067
5.8500	.118	.000
6.3000	.059	.000
7.4000	.000	.000
The test result variable(s): STSLach has at least one tie between the positive actual state group and the negative actual state group.		
a. The smallest cutoff value is the minimum observed test value minus 1, and the largest cutoff value is the maximum observed test value plus 1. All the other cutoff values are the averages of two consecutive ordered observed test values.		

6.2.5 Quantifying Anteromedial Rotary Laxity (AMRL)

The Feagin Thomas test is used to assess for AMRL and specifically assesses for vulnerabilities within the deep MCL which often accompanies ACL injuries. Not all participants included in the study had available data for the Feagin-Thomas test, this is reflected in the descriptive tables (n=58 uninjured legs, n=22 injured legs) [Table 47].

Table 47: Groupings of Participants, Sample sizes of groups, Associated number of repetitions in the tests for the Mean Range of AMRL (mm) and Variance for Each Group providing insight into the variance of drawer test outcomes among different injury types.

Injury Profile	Grouping	Number of Participants	Number of reps	Mean Range (mm) of AMRL	SD DrawDynMed
Uninjured Legs	0	58	299	9.96	3.09
ACL NO MCL	1	12	81	13.46	4.19
ACL and MCLs	2	3	22	11.33	1.96
ACL and MCLd (+/- MCLs)	3	7	39	12.31	2.81

For the Feagin-Thomas test, there was data available for 58 uninjured legs, 12 ACLs without any MCL involvement, 3 ACLs with superficial MCL involvement and without Deep MCL involvement (MCLs), and 7 ACLs with Deep MCL (MCLd) involvement. There were multiple repetitions conducted on each participant [Table 48]. The range (mm) values in absolute translation of AMRL were 9.96(+/- 3.09), 13.46 (+/- 4.19), 11.33 (+/-1.96) and 12.31 (+/-2.81) for the 4 respective injury groups. This indicates that ACL injuries with MCL injuries have more absolute AMRL in the injured leg than those without MCL involvement and all injured groups have more AMRL than the non-injured control legs.

Ratios were also calculated when looking at AMRL in order to obtain an asymmetry metric to the participant's contralateral leg, for this reason there was a different volume of data

available. There were 19 ratios for uninjured participants, 11 for ACL injured without MCL involvement, 3 ACLs with superficial MCL only and 6 ACL with Deep MCL involvement. There were multiple repetitions completed for the test on each respective cohort group [Table 48].

Table 48: Groupings of Participants, Sample sizes of groups, Associated number of repetitions in the tests for the Ratio of AMRL and Associated Distribution Profiles for each Subgroup

Injury Profile	Grouping	Number of Participants	Number of reps	Shapiro Wilk Sig. MeanMeanNorm	Shapiro Wilk Sig. MaxMaxNorm
Uninjured Legs	0	19	112	0.855	0.741
ACL NO MCL	1	11	72	0.685	0.810
ACL and MCLs	2	3	22	0.035	0.481
ACL and MCLd (+/-MCLs)	3	6	34	0.189	0.113

For both the MaxMaxNorm and the MeanMeanNorm, healthy controls have similar AMRL ratio symmetry between legs (0.982 and 0.949 respectively). For ACL participants without MCL involvement the ratios were higher albeit not statistically in comparison to the healthy control subjects (1.17 and 1.18). ACL participants with MCLs injuries yielded AMRL values non significantly higher than those without MCL involvement (1.48 and 1.44), finally those with Deep MCL involvement had the highest values of AMRL of 1.62 and 1.57 [Table 49]. An ANOVA test revealed statistically significant differences of AMRL between the 4 patient groups. Due to unequal variances and sample sizes between the population groups, the Games-Howell test was conducted to identify where the differences occurred between groups [Table 50]. Whilst the groups showed an incremental increase in AMRL with increased medial compartment laxity, the only statistical difference was found between groups 0 (Healthy control subjects) and 3 (ACL with Deep MCL involvement), which was $p=0.047$ and $p=0.023$ for the MaxMaxNorm and MeanMeanNorm respectively.

Table 49: Descriptives Statistics of AMRL Ratios for Healthy Control Subjects, ACL Injuries, and ACL with MCL Injuries

Descriptives									
Ratio Type	Grouping	Number of Participants (N)	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
RangeMaxMaxNorm	0	19	0.982	0.224	0.051	0.874	1.09	0.608	1.40
	1	11	1.17	0.332	0.100	0.944	1.39	0.616	1.70
	2	3	1.48	0.521	0.301	0.183	2.77	0.894	1.90
	3	6	1.62	0.422	0.172	1.17	2.06	0.891	1.95
	Total	39	1.17	0.384	0.061	1.046	1.29	0.608	1.95
RangeMeanMeanNorm	0	19	0.949	0.241	0.055	0.833	1.06	0.455	1.35
	1	11	1.18	0.315	0.095	0.966	1.39	0.627	1.61
	2	3	1.44	0.443	0.256	0.344	2.54	0.932	1.71
	3	6	1.57	0.356	0.145	1.20	1.95	0.922	1.88
	Total	39	1.15	0.369	0.059	1.028	1.27	0.455	1.88

Group 0 = Healthy Participants, Group 1: ACL without MCL, Group 2: ACL with MCLs, Group 3: ACL with MCLd

Table 50: Post Hoc (Games-Howell) Test for Ratios of AMRL for Different for Healthy Control Subjects, ACL Injuries, and ACL with MCL Injuries

Multiple Comparisons							
Games-Howell							
Dependent Variable	(I) RatioRIFemGrouping	(J) RatioRIFemGrouping	Mean Difference (I-J)	Std. Error	Sig.	95% Interval	Confidence
						Lower Bound	Upper Bound
RangeMaxMaxNorm	.00	1.00	-0.185	0.112	0.383	-0.508	0.138
		2.00	-0.495	0.305	0.514	-2.479	1.49
		3.00	-0.635	0.18	0.047	-1.26	-0.011
	1.00	.00	0.185	0.112	0.383	-0.14	0.508
		2.00	-0.309	0.317	0.775	-2.095	1.48
		3.00	-0.45	0.199	0.183	-1.08	0.18
	2.00	.00	0.495	0.305	0.514	-1.49	2.48
		1.00	0.309	0.317	0.775	-1.476	2.09
		3.00	-0.141	0.346	0.974	-1.69	1.41
	3.00	.00	0.635	0.18	0.047	0.011	1.26
		1.00	0.45	0.199	0.183	-0.18	1.08
		2.00	0.141	0.346	0.974	-1.406	1.69
RangeMeanMeanNorm	.00	1.00	-0.229	0.11	0.199	-0.541	0.08
		2.00	-0.495	0.262	0.424	-2.14	1.15
		3.00	-0.624	0.155	0.023	-1.148	-0.1
	1.00	.00	0.229	0.11	0.199	-0.084	0.54
		2.00	-0.266	0.273	0.775	-1.742	1.21
		3.00	-0.395	0.173	0.172	-0.932	0.14
	2.00	.00	0.495	0.262	0.424	-1.15	2.14
		1.00	0.266	0.273	0.775	-1.21	1.74
		3.00	-0.129	0.294	0.968	-1.447	1.19
	3.00	.00	0.624	0.155	0.023	0.099	1.15
		1.00	0.395	0.173	0.172	-0.143	0.93
		2.00	0.129	0.294	0.968	-1.19	1.45

*. The mean difference is significant at the 0.05 level.

Group 0 = Healthy Participants, Group 1: ACL without MCL, Group 2: ACL with MCLs, Group 3: ACL with MCLd

Effect sizes were completed to investigate the strength of relationship between AMRL and ACL and MCL injury. Omega squared (ω^2) values were chosen to represent the effect as it provides a comprehensive correction for bias and had better generalisability to the wider population [Appendix D: Laxity tables]. Effect sizes for the RangeMaxMaxNorm and RangeMeanMeanNorm were 0.332 and 0.357 respectively, both of the values are large, suggesting a strong effect of increasing MCL injury (with combined ACL injuries) on AMRL. This means that increased damage to the medial compartment significantly affects the knee's rotational laxity compared to the uninjured side.

6.3 Discussion

The laxity of a joint is dependent on the joint type and its relative anatomy. The knee is inherently unstable due to the shape and the congruency of the articulating surfaces (102). It relies on the structural integrity of the surrounding soft tissue envelope (181). Consequently, changes to the mechanical behaviours of the tissue structures such as ligament damage, can manifest in laxity changes and are more apparent in the knee than perhaps in other joints (102, 182). This study attempted to quantify the laxity at the knee joint in ACL injured participants compared to healthy control participants.

Knee laxity was quantified in the injured population and healthy control subjects using optical motion capture technology to accurately quantify the biomechanical differences between the cohorts during clinical laxity tests. This was to attain a ground truth prior to developing clinical tools which aims to aid the identification of knee injury in the clinical setting.

Measures of laxity can be calculated in different ways; absolute measurements of anterior tibial translation (ATT in millimetres) were recorded in healthy participants and those with ACL ligament injury. Clinically both legs should always be tested this allows the clinician to get a baseline of laxity for that patient(183). However, in order to obtain laxity values that considered interpersonal variability, ratio values which compared translation between health and injured limbs were calculated. For instance, difference in anatomy, the extent of damage, muscle tone, and compensatory guarding strategies are all potential reasons for such variability. One study explains that this large heterogeneity in knee laxity is due to the variability in the biomechanical function of knee ligaments: naming this as the phenomenon's of 'in situ stiffness' and 'in situ slack' (12).

In situ stiffness is dependent on fibre structure and relative anatomical orientation of the ligaments, other research supports this concept, Küpper et al (2007), report that genetic predispositions, more specifically chronic hypermobility disorders, can cause changes in the matrix proteins which in turn subsequently affects the mechanical structure of the tissues thereby deviating from the baseline level of laxity(98). 'In situ slack' refers to the degree of movement between the tibia and femur, starting from the joint's neutral posture up to the point at which the ligament starts to experience tension (12).

The results from this study, in addition to the phenomena of 'in situ slack and stiffness' as well as the well-known 3mm cut off threshold of side-to-side difference to identify ACL injuries all help support the importance of measuring laxity as an asymmetry value (ratio) as opposed to absolute measures of ATT (mm) in isolation.

There has previously been speculation as to what is the most sensitive and specific clinical test for identifying ACL injury amongst clinicians (2, 63, 67, 184, 185). Factors impacting diagnostic accuracy are examiner experience, handling variabilities, chronicity of injury, gender, and consciousness of the patient (7, 186, 187).

In this study, three different clinical tests were performed to assess anterior knee laxity; the Anterior draw, Lachman, and Anterior drawer whilst the participant was sat on the edge of the bed (a variation of the traditional anterior drawer test). Our findings align with other research which highlights the importance of completing multiple tests before deciding on ACL integrity, each test possess specific limitations (25, 188). The three tests assess ATT in different positions which changes the anatomy of the soft tissue envelope and the joint congruency as well as the muscle tone of the participant (78, 188, 189). On average the anterior drawer test provided the greatest volume of knee laxity asymmetry for ACL injured participants, however it did not consistently perform as the most effective test to assess for laxity across all participants. Possible reasons for this may include changes in participants muscle tone in certain positions, joint effusion, pain, and anatomical discrepancies. Therefore, it would be advised that clinicians complete all 3 clinical tests to identify for increased tibiofemoral anterior displacement before drawing conclusions regarding ACL integrity. The three clinical tests provide a comprehensive evaluation of knee laxity in differing degrees of knee angle and therefore provoke changes in subsequent joint congruency and residual slack in the ACL (12, 98). They also differ in the speed and force of which the clinician pulls changing the reaction of the soft tissues (78), this may be related to the amount of residual muscle activity of the patient, muscle activity during these clinical tests is explored further in Chapter 7.

Multiple repetitions of each clinical test were performed on each participant, this provided several advantages in this study, such as improving reliability by minimising variability due to patient movement, examiner technique, and guarding responses from the patient. This approach allowed for identifying consistent patterns in knee laxity, offering a more

comprehensive understanding of ACL integrity. However, while multiple repetitions were conducted to enhance data robustness, a formal analysis comparing anterior tibial translation (ATT) changes from the first to the last repetition for the same participant was not performed. Future research could explore these changes to better understand the impact of repeated testing on knee laxity assessment.

Isolated ACL injuries are rare, associated damage to the collateral ligaments, menisci, cartilage, and subchondral bone are common (190). In this study, the relationship between concomitant knee injury severity and asymmetry of ATT was investigated. Due to the relatively small sample size, participants were grouped into extent of concomitant injury by summing the number of additional ligament injuries and repeating this for meniscal injury. This meant that the effect of specific concomitant injury structures on ATT could not be investigated; due to the small sample size, if subgroups were categorised as the specifically injured concomitant structures, the subgroups would not be powered appropriately. Our results indicated that increased injury severity i.e. larger number or degree of damage to the structures stabilising the knee did not lead to increased asymmetry in ATT. Previous studies however have found people who have experienced an ACL injury with associated medial meniscal injury have increased anterior laxity (191, 192). Previous research has also found that increased laxity is also associated with an increased likelihood of capsular injuries on the anterolateral side (187, 191, 193). Whilst the findings of this study did not agree with this published research, this should be repeated on a larger population size.

It is widely accepted that in addition to joint laxity assessments, the subjective history and symptoms of the patient are integral in the triage process and can play a role in injury detection (61). The problem with using subjective history alone is that not all patients report the 'typical' patterns and symptoms of injury (25, 189), however a paper by Hardy et al noted that by using a threshold of 3 or more symptoms as reported by the 'LIMP index' could facilitate the correct identification of ACL tears 83.9 % of the time(61). Although this statistic appears promising, the relative specificity (the ability to recognise patients who have not suffered ACL injury) was low indicating that using subjective criteria alone may overload clinical services by assuming ACL injuries on many uninjured patients.

In this study, the impact of LIMP index factors on ATT was investigated in order to see if increased reported symptoms were indicative of a more objectively unstable joint. Our results

did not show a relationship between subjective history criteria and objective measures of knee laxity. Suggesting despite the diagnostic use of the LIMP index, those that score higher are not associated with greater measures of joint laxity.

The only objective method established to quantify knee laxity within the clinical setting is the KT1000, 2000, or validated devices such as the Lachmeter (174, 194). However, these devices are limited to only measuring ATT in one position, when the knee is in lower degrees of flexion such as the Lachman test, meaning there is no current evidence comparing the amount of laxity across multiple planes of movement or across different clinical stability tests, making this research the first to do so. Significant inconsistencies in the accuracy of arthrometry devices have been reported which has led to a decreased popularity in clinical practice (37, 101). Nonetheless, despite these known inaccuracies, it was deemed important that arthrometry measurements were taken for participants as it is the only tool validated as a clinical measure of knee laxity and therefore would provide an important comparator to the OMC data.

The literature suggests that a side-to-side (STS) difference of 3mm or more recorded by an arthrometer during a Lachman's test is indicative of ACL 'laxity' (77). The study firstly evaluated the diagnostic performance characteristics (DPCs) of the Lachmeter for the included participants as well as comparing this to the diagnostic ability for OMC systems when measuring ATT. DPCs were initially calculated for the Lachmeter device with the established 3mm STS threshold, an accuracy rate of 68.7% within the same examiner under controlled conditions points to a concerning lack of reliability. In comparison, when using the same threshold during the Lachman test using OMC, accuracy results were marginally superior at 71.43% for measuring ATT.

The value of 71.43% does not reflect the full diagnostic ability of OMC systems to identify ACL tears from measures of laxity. OMC provides the ability to measure laxity obtained across multiple planes for a plethora of clinical tests, further work could investigate the comprehensive ACL diagnostic ability of OMC systems by including multiplanar laxity movements into the analysis. However, as OMC systems would never be utilised as a diagnostic tool within the clinical environment, this was not conducted.

Further analysis was conducted on arthrometer data through binomial regression, incorporating data from both ACL injured and healthy control subjects was used to evaluate the capability of diagnosing ACL injuries based on STS differences. The receiver operating characteristic (ROC) curve indicated that while higher Lachmeter readings improved the model's diagnostic capacity for ACL injuries, suggesting a positive link between increased Lachmeter values and the likelihood of an ACL injury, it was recommended that a more conservative STS threshold of 1.35mm be adopted to optimise sensitivity and specificity. However, such a conservative threshold, while potentially minimizing false negatives, could lead to a significant rise in false positives. This low threshold would place an unnecessary burden on healthcare systems by identifying a higher prevalence of ligamentous injuries than exists in reality. This delicate balance underscores the need for further refinement in diagnostic criteria and methodologies to ensure accuracy while avoiding over-diagnosis. The value area of 0.735 from the ROC curve would generally indicate that the Lachmeter is not a robust diagnostic tool. These findings are consistent with other research which also indicates reflects poor diagnostic ability of the arthrometer (37, 195, 196), reinforcing the Lachmeter's limitations as a diagnostic tool for anterior cruciate ligament (ACL) injuries.

The ACLs secondary role in knee stability is to prevent tibiofemoral external rotation (29). The MCL contributes to valgus stability and plays a primary role in maintaining anterior-medial rotary stability (30). MCL are concomitantly involved in up to 42% of ACL injuries (31), they have good healing capacity and are rarely operated on in isolation. Unidentified MCL injuries and subsequent rotational laxity are known to have consequences on long term functionality (10, 29, 32). Residual and unresolved rotational laxity contributes to poor knee functioning and ACL graft failure (33). There is no current method to clinically measure anterior tibial translation and rotational laxity simultaneously, however this coupled movement is problematic and associated with varied patient outcomes (34). Since correcting AMRL is integral to patient's functional outcomes, the importance of measuring, identifying is important.

Slocum and Larson (SL) were the first to identify the phenomenon of AMRL in the 1960s and developed a test to assess components of rotary laxity (35). The Feagin Thomas test; a novel way of assessing AMRL uses the components of the SL test with added handling variation which provided a new refined method to test for AMRL. The main difference being that the

patient sits on the edge of the treatment plinth allowing greater knee flexion in a natural sitting position whilst maintaining the advantage of getting the proprioceptive feedback of the plinth to facilitate a more relaxed posture.

In this cohort of injured participants, ACL injuries without MCL involvement showed a small increase in AMRL, MCL and particularly deep MCL injuries increased the AMRL by up to 62%, indicating that both the superficial and deep MCL fibres contribute to anteromedial rotary laxity. Whilst many studies have looked in vitro at rotational laxity components in the knee (36, 37), very few have investigated the laxity in the conscious patient. Our results demonstrate that the Feagin Thomas test is both sensitive and specific in identifying AMRL which manifests in concomitant ACL and MCL injuries, especially those with deep fibre involvement. This suggests it has a role in the assessment of the injured knee.

6.4 Limitations

The process of quantifying knee laxity within this study faced several limitations. All methods of quantifying ATT are subject to error and inaccuracies, this means there is no concrete way to validate OMC knee laxity data as there is no true gold standard way of determining this clinically. Arthrometry is subject to handling error, and poor repeatability. Subjective means of laxity assessment are subject to large variation depending on examiner interpretation. Radiological verification such as dynamic MRI is a method to show dynamic morphology changes; however, there is variability in the interpretation of dynamic MRI results, especially when used for assessing functional joint motion. Different studies have reported varying results when comparing dynamic MRI to static MRI measurements, indicating that the accuracy and reliability of dynamic MRI can be inconsistent. Moreover, the technical demands and high costs associated with dynamic MRI make it less accessible for routine clinical use, limiting its application primarily to research settings or highly specialised cases (137).

Furthermore, the clinical tests within this study were conducted by a single examiner. This approach raises concerns regarding the generalisability of the findings, as it does not capture the potential variability in assessment that might occur with multiple examiners. In clinical practice, different examiners may introduce variations in how tests are performed, potentially affecting the consistency and reliability of the measurements of knee laxity. Future work is

required to explore interrater reliability of the ATT measures obtained with the motion capture system.

Another significant limitation is related to the nature of ACL injuries themselves. These injuries rarely occur in isolation; damage to surrounding ligamentous and meniscal structures is common. However, due to the constraints of the studies sample size, it was not feasible to perform detailed analysis on the impact of individual concomitant injuries. A larger patient cohort would be required to statistically power such analyses, which would allow for a more precise understanding of how specific additional injuries influence laxity measurements and outcomes.

6.5 Summary

This study underscores critical biomechanical distinctions in laxity at the knee joint between ACL-deficient patients and healthy controls. The findings highlight the complex nature of clinical laxity assessments and the interpersonal variability within ligamentous behaviour. It underscores the necessity of personalised evaluations by measuring ATT as asymmetry between legs rather than as an absolute value. Despite the anterior drawer (AD) test showing on average more asymmetry in anterior laxity in comparison to other tests, this is not consistent for all individuals, illustrating the need for a comprehensive, multifaceted approach to clinical evaluation before determining the extent of injury.

The comparative analysis between traditional arthrometry and advanced VICON motion capture systems illuminates the substantial benefits that motion capture technology offers in the ability to capture knee laxity across multiple planes of movement. By enabling a detailed, multi-planar analysis, VICON systems advocates for potential to integrate objective diagnostic tools capable of measuring laxity into clinical settings. Such metric could improve the diagnosis of ACL injuries.

Furthermore, our insights into rotational laxity have enriched our understanding of ACL deficiencies, revealing the need to adjust acute knee assessments to identify and manage concomitant MCL injuries. This study advocates for the inclusion of assessments like the Feagin Thomas test, which is both sensitive and specific to anteromedial rotary laxity, particularly in cases involving deep MCL fibres. Addressing such rotational laxity is crucial, as

unidentified, or untreated issues can lead to poor knee functionality and influence the success of ACL grafts.

Overall, this research contributes to a paradigm shift in how ACL injuries are diagnosed and managed, emphasising the potential to integrate diagnostic technologies and comprehensive assessment strategies to enhance patient outcomes and early diagnosis.

7 The Effects of Muscle Guarding During Laxity Assessment

7.1 Introduction

The two major obstacles to assessing joint integrity in the ACL deficient person is joint effusion and muscle guarding (34). Both factors can contribute to reduced diagnostic accuracy and subsequent management delays (35).

Joint effusions can persist for first 3 months following an injury (197). The effused joint is harder to assess and manipulate as it naturally stiffens the joint, it is accompanied by painful inflammatory markers (95). The combination of pain and swelling from the injury can cause people with ACL injuries to display features of ‘muscle guarding’ during clinical assessment (198). ‘Muscle guarding’ is the involuntary protective mechanism of muscle contraction from the patient to protect the vulnerabilities caused by the injury (121, 198).

There is a synergistic relationship between knee effusion and muscle guarding, with a decline in effusion being negatively correlated with muscle guarding. These factors are particularly exacerbated during the acute phase of injury. It has been observed that knee laxity test sensitivity increases by 43% in chronically injured ACL patients (67). Muscle guarding, a subconscious protective mechanism, is absent in unconscious patients. This was demonstrated in a study where the sensitivity of the anterior drawer test in awake ACL-injured patients was compared to the same test administered under anaesthesia. The test sensitivity increased significantly from 49% to 78% when patients were anaesthetised (67).

By measuring the electrical activity produced by muscle fibres, EMG sensors can provide objective, real-time data on the magnitude and source of muscle contractions (199). This capability provides the potential to enhance the reliability of joint laxity assessments by providing information on the protective muscular contractions (121, 198).

EMG data capture is highly sensitive to various external factors that must be carefully controlled to obtain accurate and reliable signals. Even with measures in place to minimise signal interference, additional data handling and signal processing techniques are necessary to address several challenges. For example, baseline noise from the muscle itself, noise introduced by the assessor, and external interference from other electronic devices or technologies operating nearby can all disrupt or contaminate the true signal, requiring careful filtering and processing to isolate meaningful data (199, 200). Muscle crosstalk—where

signals from adjacent muscles interfere with the target muscle's signal—can lead to inaccuracies in data interpretation. The placement and configuration of sensors are also critical, as incorrect placement can result in poor signal quality or misrepresentation of muscle activity (200). Further complicating EMG data processing is the lack of standardised protocols for calibration and data normalisation(200). There is also significant variability in how researchers and clinicians interpret muscle activation patterns, particularly in defining and quantifying phenomena like muscle guarding. This lack of consensus can lead to inconsistencies in data interpretation and challenges in comparing results across studies.

Muscle activity is traditionally expressed as a percentage of the participant's maximum voluntary contraction (MVC). However, in injured cohorts, pain inhibits their ability to produce an MVC reflective of their true capability (201, 202). Therefore, in this study, muscle activity was reported relative to the activation threshold, expressed as a multiple of the participant's resting tone. Given the complexities of EMG data and the absence of a standardised quantitative definition of muscle guarding, the "ABC of EMG" by Konrad (2005) was used as a reference for processing the data. This methodology was then adapted to meet the specific requirements of this study's protocol and subsequent data analysis needs. (200).

Whilst there has been an abundance of studies of measuring EMG activity within the ACL cohort (199, 203-205), there has been none to date measuring muscle reactivity during clinical assessment of knee laxity. Implementing EMG technology in clinical and research settings could lead to more information relevant to diagnostics and subsequent improved patient outcomes by more accurately defining and mitigating the effects of muscle guarding.

In addition to investigating the kinematic changes in knee laxity between ACL injured and healthy control subjects in Chapter 6. This chapter focuses on the EMG measurement of muscle guarding, EMG data was collected alongside the optical motion capture data in order to investigate the effects of muscle guarding.

Research Question:

How do we measure muscle guarding with EMGs when testing ACL laxity?

Sub-questions:

- Do ACL injured patients 'guard' more than the healthy control group and how does this change between muscle groups and clinical tests?

- Is there a correlation between muscle guarding and knee laxity?

7.2 Methods

Full details of the study protocol and EMG sensor placement can be found in 5.2.14 and 5.2.7 respectively. Data was collected in the biodynamics lab alongside VICON and IMU data collection. Participant details and recruitment are outlined in section 5.2.10.

This specific study aimed to elucidate the relationship between muscle activation, as indicated by EMG data relative to the EMG threshold, and anterior tibial translation reported as a proportion, across various muscle groups and clinical tests. The analysis was divided into two primary components: the evaluation of activation differences between ACL injured participants and healthy control subjects using Chi-squared tests, and the investigation of the linear correlation between muscle activation and anterior tibial translation.

7.2.1 Processing EMG Activity

Often, EMGs are reported as a percentage of the maximum voluntary contraction (MVC), normally 30% indicates muscle activity, however the injured population are frequently unable to produce an MVC due to pain after the injury (201, 202). This was reflected in the initial data analysis which indicated much lower MVC EMG amplitudes in ACL injured legs than in their contralateral healthy leg. It was also noted that the EMG amplitudes were higher during the walking and functional trials than those recording during an MVC of the injured leg. This suggests that testing the MVC of the injured leg is not a true reflection of the muscle capacity of that respective leg. Reporting muscle activity as a measure relative to their 'resting activity', therefore, deemed preferable as this avoids biasing results towards false-positive activation.

This is otherwise known as 'threshold definition by multiple SD of EMG baseline noise' (200). This approach allows the muscle to be defined as being on or off which in the context of this work was considered as the patient guarding or not. For us to consider the patient as 'guarded' the signal had to be ≥ 1.00 which signified the activation threshold (200).

The raw EMG signal was run through a bandpass filter between 10-500Hz using a 2nd order Butterworth filter, this range isolates the relevant signal components, enhancing the accuracy of muscle activity detection. The data was then smoothed by finding a root mean squared for each data point over 100ms window for the entire trial. This smoothing technique reduces short-term fluctuations and noise, providing a clearer representation of the muscle activation

patterns. The RMS method is particularly effective for EMG analysis as it quantifies the signal amplitude, offering a robust measure of muscle contraction intensity over time.

For each muscle group on the respective leg for the patient being analysed, an automated search was conducted on all the trials to find the lowest EMG signal. A frame window of 100ms (50ms) each side of that point. The mean (μ) and standard deviation (σ) of this window were calculated which were considered the patient's 'resting tone'.

There is no universal threshold criterion for defining muscle activity onset, though most literature suggests using a range within 1-3 standard deviations (SD) (206). However, it is recognised that signals from modern surface EMGs are relatively noise-free, which has led some researchers to advocate for higher thresholds—up to 8 SDs—for more reliable results (200). Other algorithms have even used thresholds as high as 10 times the mean level of EMG activity (207).

When a smaller SD is used the threshold of determining the signal as being 'on' is decreased, therefore the chance of receiving a type 1 error (muscle is identified as active when it is not) is increased, when higher SD are used there is then an increased chance of getting a type II error (muscle not being identified as active when it is in fact) (206).

Guarding is described as involuntary muscle activation associated with apprehension, pain and swelling post-acute ligamentous injury, it prevents joint movement and stiffens the joint in attempt to protect any damaged structures (208, 209). For this analysis, a more conservative approach to define the activation and therefore a higher SD of 8 was used. For completeness the same analysis using a threshold of 3SDs was also conducted which revealed similar outputs and can be found in Appendix E: EMG Analysis using a 3 S.D Threshold for Establishing Activation Threshold.

$$\text{Activation Threshold} = \mu \text{ of resting tone} + 8 \text{ Standard Deviations } (\sigma)$$

This data was run through another bandpass filter between 10-200Hz using a 2nd order Butterworth filter. Outliers were removed using a threshold of the 95th percentile. Areas of no signal or abnormal signal which would indicate EMG detachment, were removed.

The second issue that required consideration was the placement of the sensors and the clinical handling necessary to complete the tests. While sensor placement was optimised to

avoid contact by the clinician, this was not always feasible. Accidental handling of the sensors had to be managed during post-processing. To address this, a zero-crossing threshold was created to detect and handle any soft tissue artefact movement external to the EMG, thus managing erroneous spikes in activity.

The zero-crossing threshold was set at 0.05, meaning that if the signal did not cross zero within 5% of the 100ms window, the data would be considered as 'not a number' ('NaN'). For segments with sufficient data (fewer than 100 NaNs), the script checks for any NaNs. If NaNs are present, the script employs the 'fillmissing' function with the 'next' method to replace NaNs. The 'next' method fills each NaN with the next non-NaN value found in the array, thereby interpolating missing values based on subsequent data points. This approach aims to maintain the continuity and integrity of the signal for accurate analysis.

A time normalised mean plot of all the filtered and processed repetitions were then calculated to see the average activation pattern of the participant (Figure 45). All plots were manually screened for each participant to do a final check for any signal errors.

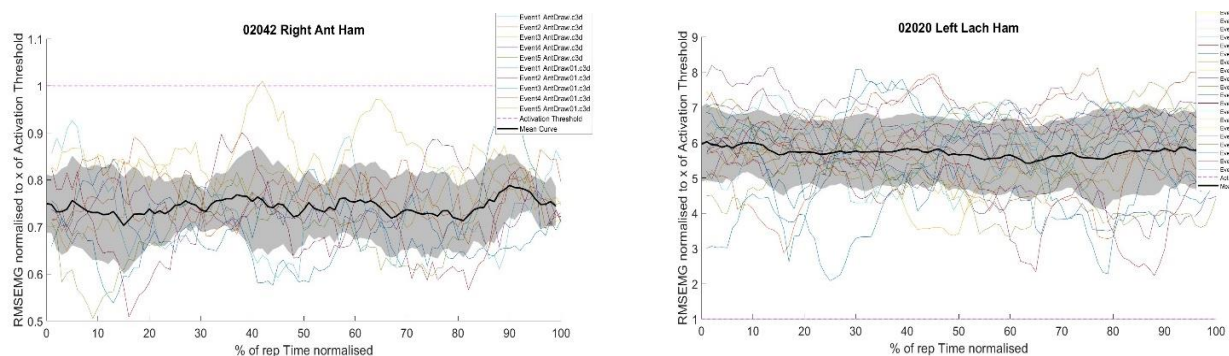


Figure 45: Example of EMG Processed EMG Signals with Time Normalised Means. (Left=Not guarded, Right=guarded)

If signals did not change much within the reps throughout the trial, an average EMG reading was determined. The initial part of the analysis required each participant to fall into a binary output classification of being considered as 'guarded' ($AT \geq 1$) or 'not guarded' ($AT < 1$).

During each clinical test, for each muscle group, percentages were then calculated to determine the proportion of patients being considered as 'guarded'. The injured population was compared to the healthy control group by a chi squared analysis, this was conducted to see if the two strata were significantly different within their 'guarded' muscle.

The second part of the analysis evaluated the relationship between muscle guarding and associated ATT.

7.3 Results

7.3.1 Evaluating Muscle Guarding Response to ATT Clinical Tests

As outlined in the methods section 7.2.1, participants were considered as being guarded or not-guarded depending on whether their muscle activity superseded the activation threshold. Frequencies (n) and percentages (%) for all three clinical tests of guarded and not guarded participants for the injured and healthy cohorts were subsequently established [Table 51 and Table 52].

Table 51: Percentage (%) of Participants Considered as Guarded for Each Muscle Group During the Respective Clinical Test

Test	Stratum	Percentage of Patients considered as being 'Activated' (%)		
		Quadriceps	Hamstrings	Gastrocnemius
AD Test	Injured	13.7	39.1	15.0
	Healthy	4.17	11.4	17.1
LM test	Injured	12.5	40.0	34.8
	Healthy	5.56	16.9	11.3
ADSOEOB Test	Injured	4.55	23.8	9.52
	Healthy	8.47	16.4	9.09

Table 52: Frequency of Participants Considered as Guarded and Not Guarded for Each Muscle Group During the Respective Clinical Test

Test	Stratum	Frequency of Patients considered as being 'Activated' (%)					
		Quadricep Activated	Quadricep Not Activated	Hamstring Activated	Hamstring Not Activated	Gastrocnemius Activated	Gastrocnemius Not Activated
AD Test	Injured	3	19	9	14	3	17
	Healthy	3	69	8	62	12	58
LM test	Injured	1	23	10	15	8	15
	Healthy	9	63	12	59	8	63
ADSOEOB Test	Injured	1	21	5	16	2	19
	Healthy	5	54	9	46	5	50

In order for chi-squared analysis to be calculated, expected frequencies were calculated to determine the degree to which the observed data deviates from what would be expected under the null hypothesis [Table 53].

Table 53: Expected Frequencies of Participants Considered as Guarded and Not Guarded for Each Muscle Group During the Respective Clinical Test

Test	Stratum	Expected Frequencies					
		Quadriceps Activated	Quadriceps Not Activated	Hamstrings Activated	Hamstrings Not Activated	Gastrocnemius Activated	Gastrocnemius Not Activated
AD Test	Injured	1.40	20.60	4.20	18.80	3.33	16.67
	Healthy	4.60	67.40	12.80	57.20	11.67	58.33
LM test	Injured	2.50	21.50	5.73	19.27	3.92	19.09
	Healthy	7.50	64.50	16.27	54.73	12.09	58.92
ADSOEOB Test	Injured	1.63	20.37	3.87	17.13	1.93	19.07
	Healthy	4.37	54.63	10.13	44.87	5.07	49.93

Chi-squared tests revealed differences in activation between ACL injured and healthy control subjects across different muscle groups and clinical tests [Table 54]. In the anterior drawer test, a significant difference ($p=0.0029$) was observed in the hamstring muscle group, indicating a statistically significant higher proportion of activation in injured individuals compared to healthy control subjects.

The Lachman test showed significant differences in both the hamstrings and gastrocnemius muscle groups ($p=0.018$ and $p=0.0091$), further supporting the notion of differential activation patterns between injured and healthy populations [Table 54]. Conversely, the ADSOEOB test did not demonstrate any significant differences across the muscle groups examined, with p-values exceeding the 0.05 threshold in all cases [Table 54].

Table 54: Chi Squared Values and Associated Significance Levels to Evaluate the Differences in Guarding Between Stratus for Each Muscle Group During the Respective Clinical Test

Test	Stratum	Chi Squared and Significance Levels between Stratus					
		Quadriceps		Hamstrings		Gastrocnemius	
		Activated	Not Activated	Activated	Not Activated	Activated	Not Activated
AD Test	Injured	Chi Square: 2.53		Chi Square: 8.89		Chi Square: 0.052	
	Healthy	P value 0.112		P Value:0.0029		P Value:0.820	
LM test	Injured	Chi Square: 1.34		Chi Square: 5.585		Chi Square: 6.801	
	Healthy	P value 0.247		P Value:0.018		P Value:0.0091	
ADSOEOB test	Injured	Chi Square: 0.36		Chi Square: 0.561		Chi Square: 0.003	
	Healthy	P Value: 0.549		P Value:0.454		P Value:0.956	

****Highlighted values were those which yielded statistically significant results between cohorts****

7.3.2 Evaluating the Relationship Between Muscle Guarding and Laxity

Figure 46-Figure 54 show the linear correlation between muscle activation and anterior tibial translation, this provides insights into the strength and direction of relationships across different tests and muscle groups. The anterior drawer test exhibited a slight but non-significant positive linear relationship for the Quadricep and Hamstring and Gastrocnemius muscle groups [Figure 46, Figure 47 and Figure 48].

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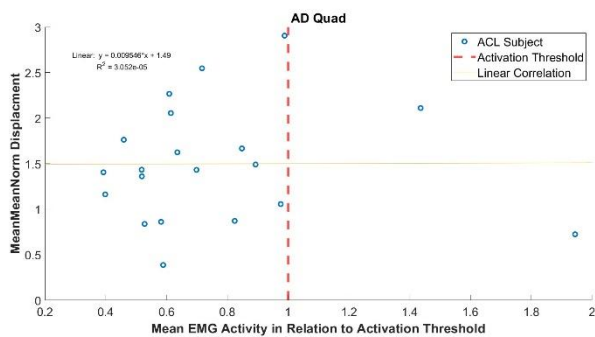


Figure 46: Relationship Between ATT and EMG values for the Quadriceps during the Anterior drawer Test. Showing no relationship of $y = 0.009546x + 1.49$ and $R^2 = 3.052e-05$

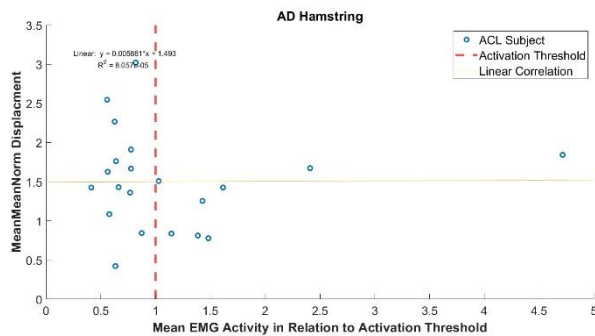


Figure 47: Relationship Between ATT and EMG values for the Hamstrings during the Anterior drawer Test. Showing no relationship of $y = 0.005881x + 1.493$ and $R^2 = 8.057e-05$

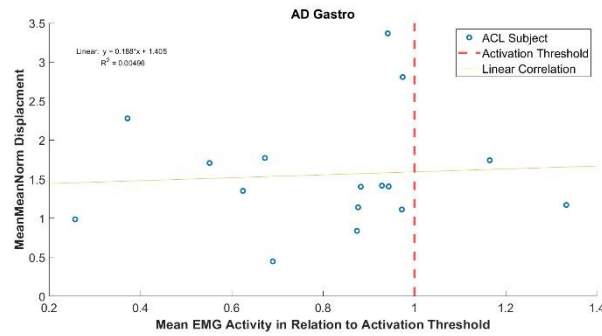


Figure 48: Relationship Between ATT and EMG values for the gastrocnemius during the Anterior drawer Test. Showing a weak positive relationship of $y = 0.188x + 1.405$ and $R^2 = 0.00496$

The Lachman test in contrast revealed a negative linear relationship for the Quadriceps, Hamstrings, and Gastrocnemius muscle groups, indicating a weak inverse relationship between muscle activation and anterior tibial translation [Figure 49, Figure 50 and Figure 51]. Thereby indicating that as laxity increased during the Lachman test, muscle activation decreased for all 3 muscle groups.

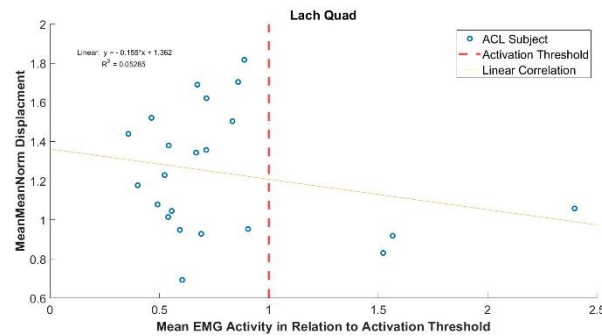


Figure 49: Relationship Between ATT and EMG values for the Quadriceps during the Lachman Test. Showing a weak negative relationship of $y = -0.155x + 1.362$ $R^2 = 0.05285$

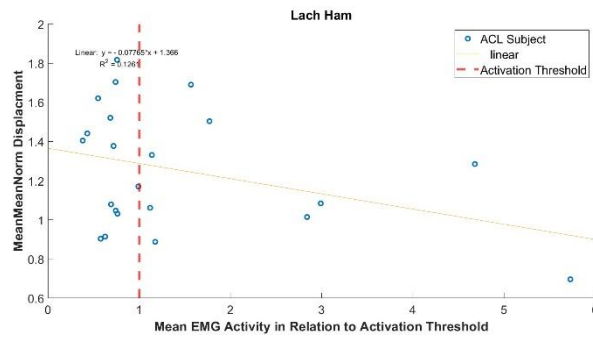


Figure 50: Relationship Between ATT and EMG values for the Hamstrings during the Lachman Test. Showing no relationship of $y = -0.07765x + 1.366$ and $R^2 = 0.1261$

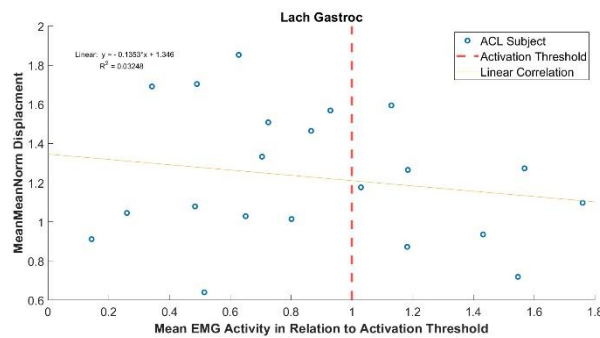


Figure 51: Relationship Between ATT and EMG values for the Gastrocnemius during the Lachman Test. Showing no relationship of $y = -0.1353x + 1.346$ and $R^2 = 0.03248$

The linear correlation analysis for the ADSOEOB Test showed weak positive relationships between muscle activation and anterior tibial translation for the Quadriceps and Hamstring muscle groups, as evidenced by their respective R squared values [Figure 52 and Figure 53]. This reflects that as anterior knee laxity increases, so does the muscle activity within the quads and hamstrings. However, the relationship between anterior laxity and gastrocnemius muscle activity presented a weak negative relationship [Figure 54].

No results revealed strong relationships between the muscle activation and laxity, this underscores the nuanced and potentially complex relationship between muscle activation patterns and anterior tibial translation in the context of injury

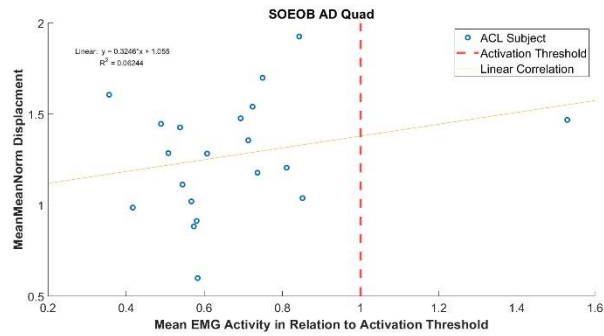


Figure 52: Relationship Between ATT and EMG values for the Quadriceps during the Anterior drawer Sat on Edge of the Bed Test. Showing a weak positive relationship of $y=0.3246x+1.055$ and $R^2= 0.06244$

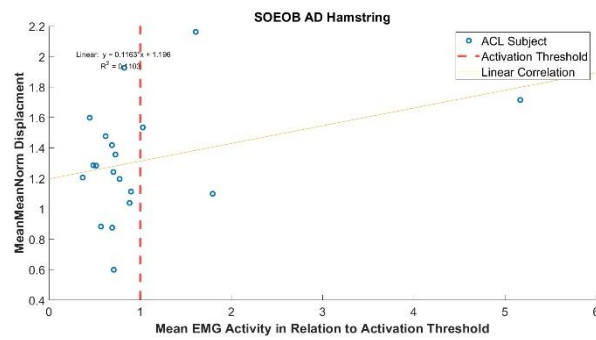


Figure 53: Relationship Between ATT and EMG values for the Hamstrings during the Anterior drawer Sat on Edge of the Bed Test. Showing a weak positive relationship of $y= 0.1163x+1.196$ and $R^2= 0.1103$

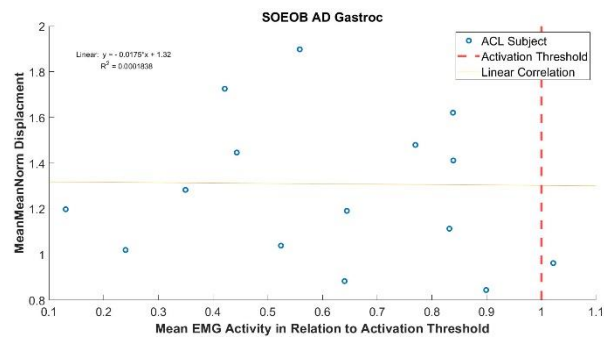


Figure 54: Relationship Between ATT and EMG values for the Gastrocnemius during the Anterior drawer Sat on Edge of the Bed Test. Showing no relationship of $y= -0.0175x+1.32$ and $R^2= 0.0001838$

7.4 Discussion

Muscle guarding has historically been theorised as a contributing factor in determining knee laxity (187), however there has been limited published research to quantify and test this hypothesis. When assessing for ligamentous integrity, the aim is to make the patient relax in order to minimise the muscular contributions which may prevent or restrict the amount of passive laxity induced to the knee (98). This reduces muscular resistance that could modify the degree of passive laxity in the knee (94). Although all three clinical tests measure ATT, each test targets specific structures within the knee. The rationale behind using different tests is twofold: first, altering the patient's position changes the tension in the soft tissue envelope around the joint; second, it modifies the resting tone of the surrounding muscle groups, providing a comprehensive assessment of knee stability (210, 211).

Statistically significant differences were observed between ACL injured and healthy control subjects within the medial hamstrings in the AD and LM test, and the medial gastrocnemius in the LM test. Direct comparisons cannot be drawn with previous research, as very limited research has investigated EMG activity during passive laxity testing in ACL injured cohorts. Despite this, these findings align with other literature that has found increased activity in the hamstrings and gastrocnemius during functional tasks post ACL injury (212, 213). The increase of muscle activity in these groups had been postulated in the literature to be compensatory for the structural loss of the ACL by inhibiting passive laxity (214-216) (217, 218).

In this study, the injured participants had increased activity in all muscle groups when compared to the healthy cohort. It is noted that quadriceps activity remained relatively low amongst both cohorts of participants across all clinical tests. Past research has indicated that quadriceps decreases in activity post-ACL injury, this attributed to the atrophy associated acutely with this patient group (216, 219). Our findings align with these studies, suggesting that despite overall increased muscle activity in the hamstrings and gastrocnemius, the quadriceps do not exhibit significant increased compensatory activation post-injury.

In addition to the above findings, muscle activity was lower across all muscle groups within the ACL injured cohort in the ADSOEOb test in comparison to the AD and LM test. Clinically, the ADSOEOb is a new variation of the AD test, the hypothesised benefit of this test is that a neutral seated position which mimics everyday posture allows the patient to be more at ease.

Guarding has been postulated to be insufficient muscle relaxation (220), a previous study found that when in a relaxed position muscle activity was kept to a minimum when monitoring with EMG(221), therefore we hypothesised that the proprioceptive feedback from the bed combined with a natural supported seating would lead to a lesser 'guarding' response. The results from this study supported this theory.

The findings from this study suggest that different clinical testing to provoke anterior knee laxity did appear to cause altered muscle activity of the hamstring and gastrocnemius, meaning that assessing ATT different positions does provide benefit in altering the guarding response of the patients, therefore highlighting the importance of comprehensive testing of ligamentous laxity before determining pathology.

Despite showing that ACL injured participants show increased muscle activity in their hamstrings and gastrocnemius during the AD and LM test in comparison to their non-injured counterparts, there was no significant relationship in the ACL injured population between 'muscle guarding' and anterior laxity. Meaning that whilst activity rises in the muscles of injured people, it does not impact ATT. This disputes the theories of Solomonow et al. and MacWilliams et al. who theorised that increased hamstring activity led to a decrease in ATT in injured groups (219, 222). Only one other study has investigated EMG Activity during any attempt to quantify ATT; during arthrometer testing, Kupper et al found increased gastrocnemius activity compared to other muscle groups during the Lachman's test, however this study has a very small sample size of healthy controls (n=5), it also used an activation threshold of 5% of MVC to establish muscle guarding rather than the approach used in this study (98). This begs the question on how defining muscle guarding impacts findings. More research is necessary which investigates muscle guarding through using varied activation thresholds before concrete conclusions are established.

In order to get an accurate representation of the participants muscle activation, multiple repetitions were performed for each clinical test on each subject. Repeating the tests multiple times allows for averaging out any anomalies or variations in ATT or muscle activity, thus providing a more accurate and reliable representation of the participants' true laxity or muscle activation patterns. Variability in ATT was observed across repetitions, this is reflected within the differences of maximal asymmetry ratio displacement values ('MaxMaxNorm') in comparison to the mean asymmetry ratio displacement values ('MeanMeanNorm') values.

However, the EMG signal appeared to change minimally from the 1st to the last repetition, examples of this are shown in Figure 45. This figure suggests that muscle activation remains consistent across the duration of the tests for both the 'guarded' and 'non-guarded' participant, rather than increasing or decreasing as the repetitions continue.

While our findings did not reveal a relationship between knee laxity and muscle guarding and given the lack of pre-existing research in this area, few comparisons can be drawn. Other research indicates that laxity sensitivity values are 29% higher for patients under anaesthesia and 43% higher in the chronically injured population (67). Both anaesthesia and lack of consciousness reduce muscle activity, thereby diminishing the guarding response. This suggests that muscle contributions significantly impact diagnostic accuracy during clinical testing in acutely injured, awake patients.

In theory, this could dispute our findings, but further research is needed to explore this inconsistency. Our study did not reflect these broader findings, indicating a need for additional investigation into the role of muscle guarding in diagnostic accuracy. Further work necessitates exploring different methods to quantify muscle guarding, such as using a percentage of maximum voluntary contraction (MVC) or establishing different activation thresholds. It is also essential to test larger patient populations that encompass varied injury timeframes, such as acute versus chronic injuries, and to compare results between awake and anaesthetised patients.

7.5 Limitations

There are several considerations when working with EMG sensors in the context of this research. One significant challenge is the lack of a universally accepted definition of 'muscle guarding' in the literature. Traditionally, EMG readings are recorded as a percentage of the Maximum Voluntary Contraction (MVC). However, when participants are injured, their ability and motivation to achieve an MVC may not fully reflect their physiological maximum potential, which could impact the accuracy of this method. In this study, as justified in section 7.2.1, muscle guarding was defined as the participant exceeding an activation threshold that was a multiple of their resting tone.

The importance of filtering, calibrating, and processing EMG signals is paramount, as these steps significantly influence the outcomes and interpretations derived from the data. While

this study did not find a clear relationship between EMG activity and knee laxity, this could be due to the complexities involved in signal management. EMG analysis requires sophisticated techniques that can vary in their application, highlighting the need for continued refinement and standardization in EMG processing methods to ensure reliable and consistent results. By addressing these considerations, we aim to enhance the accuracy and reliability of future research in this area.

7.6 Conclusions

This study demonstrated that different clinical tests designed to provoke anterior knee laxity alter muscle activity, particularly in the hamstrings and gastrocnemius muscles, in ACL-injured patients. Significant differences in muscle activity were observed between ACL-injured and healthy control subjects during the Anterior drawer (AD) and Lachman (LM) tests. Despite increased muscle activity in the injured participants, quadriceps activity remained low, reflecting previous findings on post-ACL injury muscle atrophy.

Notably, no significant relationship was found between muscle guarding and anterior tibial translation (ATT), challenging theories that increased hamstring activity decreases ATT. However, it is noted that there are many obstacles which must be considered when processing and measuring EMG signals to define muscle activation, these can alter the conclusions drawn. Future research should explore different methods to quantify muscle guarding, including various activation thresholds, and test larger, diverse patient populations to better understand the role of muscle activity in knee laxity and improve diagnostic accuracy.

8 Gait Analysis Using Motion Capture

8.1 Introduction

This chapter focuses on the kinematic variations observed as a result of ACL injuries with respect to gait analysis as measured by motion capture systems. Alterations in functional kinematics are one of the most common findings post ACL injury (121). Gait analysis allows clinicians to observe patients' natural movement patterns, which can reveal abnormalities that might not be apparent during assessments of knee laxity (223). This is particularly important for ACL injuries, where alterations in gait can signify changes in joint stability and muscle strength. For example, patients with ACL deficiencies often exhibit angular joint change which can affect load distribution, this can be a precursor to further joint degradation or re-injury (224).

Changes within gait patterns can be a consequence of neuromuscular adaptations due to pain or swelling in the acute stages, mechanical compensatory strategies can then occur once the initial symptoms have resolved in attempt to stabilise the knee (225). Many papers have evaluated gait deviations in ACL-deficient patients (150, 173, 226, 227), however gait analysis is not often used for diagnostic purposes. However, the inclusion of a functional analysis into the patient assessment has the potential to build a comprehensive, personalised, clinical picture of their presentation that could aid management.

A commonly described gait pattern in the ACL deficient patient is the 'pivot shift avoidance' gait, this is where the participant avoids weight-bearing in the last 20 degrees of extension to prevent subluxation of the knee which is subjectively reported as 'giving way' (61), this is explained in detail in 4.5. This 'giving way' is both painful and traumatic, it can elicit microtrauma within the knee giving rise to inflammation and effusion and may act as a precursor for secondary meniscal and osteochondral injury (2, 25, 26, 228). The adopted gait pattern is a compensatory strategy to prevent this painful inflammation (118).

The methods in this chapter involve detailed gait assessments using optical motion capture systems to analyse knee joint angles to capture triaxial movement across various stages of the gait cycle. This chapter presents a kinematic functional analysis of the injured ACL leg compared to the contralateral uninjured leg to evaluate nuanced compensatory changes. Additionally, it investigates differences within the ACL-injured population by comparing acute

and chronically injured participants. This chapter aims to clarify the complex interplay between knee kinematics and ACL integrity, enhancing our understanding of the compensatory mechanisms triggered by ACL injuries.

Research Question:

What are the biomechanical differences in knee angles between ACL injured and Healthy control Patients during walking?

Sub-questions:

- Are there significant differences in gait between the injured ACL leg, the healthy contralateral leg and the healthy cohorts?
- Are these differences magnified in the acutely injured cohort?

8.2 Assessment of gait

The same marker protocol and patient population described in chapter 5 was used for the gait analysis. A full data set was obtained for all participants. Participants were instructed to walk at their normal walking speed, analysis took place over the length of the lab (6m). Participants were instructed to walk the length of the laboratory at least 3 times.

Custom MATLAB processing pipelines were ran on the gait data to segment it into individual gait cycles and to calculate knee joint angles. Segmenting the data into gait cycles allowed time normalisation, these time normalised cycles were fed through SPM: a software which evaluates the differences between cohorts across data at each relative time normalised point. Mean gait cycles were calculated for each participant's respective leg, these mean gait cycles were used for comparative statistics. An ANOVA test was first run between all 3 cohorts for each plane of movement to evaluate the overall variances throughout the cycle, after this Independent T-Tests were run between all groups to see where these differences lie. Knee angles throughout the gait cycle were compared within the cohorts, their diagnostic use was evaluated.

When analysing gait the participants knees were divided into 3 cohorts based on their joint health, the ACL injured leg (ACLI)(n=25), the healthy leg of the ACL injured participants (HLI) (n=23), and the healthy legs of the healthy control cohorts (HC)(n=52).

8.3 Results

8.3.1 Kinematic Variations Within the Sagittal Plane

The ANOVA comparing the knee flexion angle between the 3 cohorts revealed the largest significant differences ($P < 0.001$) between approximately 25-50% of the gait cycle, this is predominantly in the toe-off phase where those with injured legs were in higher degrees of knee flexion than the HLI and healthy control subjects groups [Figure 55]. This was demonstrated in the mean values, where the spread of the data of the ACL injured group was towards a greater knee flexion angle compared to the other two cohorts [Figure 55].

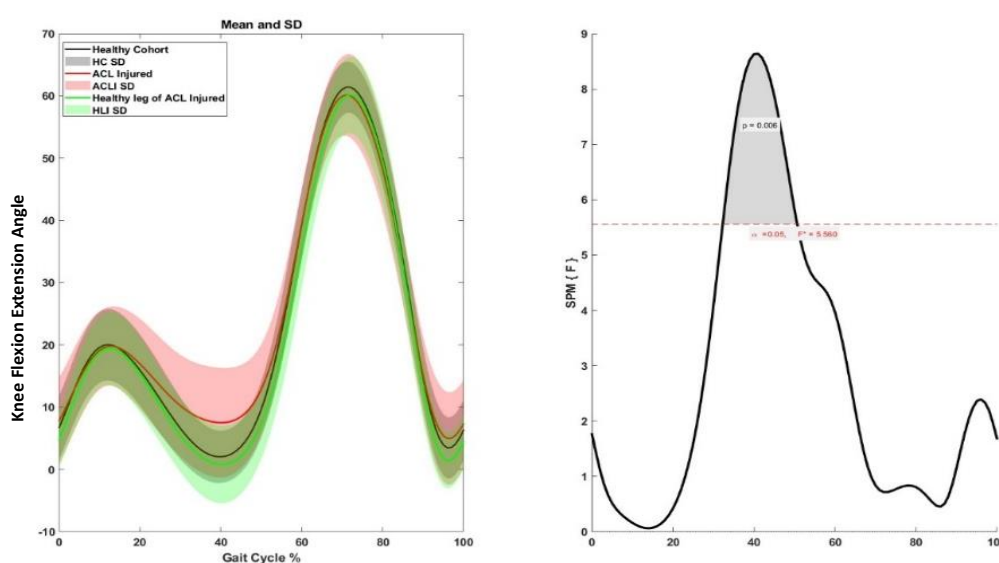


Figure 55: ANOVA to Analyse Variance of Knee Flexion Angle Between ACL Injured, Healthy Leg of ACL injured and Healthy Control Subjects

Independent T-Tests were then run between 2 groups for each comparison variation. There were no statistically significant differences between the HLI and the healthy control subjects groups [Figure 56]. Statistically significant differences ($p = 0.034$) were reflected between the ACL injured and the healthy control subjects' groups throughout the mid stance and toe off phase of gait [Figure 57]. However, the T-test between the ACL injured, and the HLI cohorts revealed the largest differences ($p = 0.013$) [Figure 58], the contralateral uninjured leg showed increased leg extension during the weight bearing phase in comparison to the uninjured healthy control cohort. Therefore, during the mid-stance and toe off phase of gait with differences of approximately 8 degrees were found between the ACL injured and the HLI cohorts.

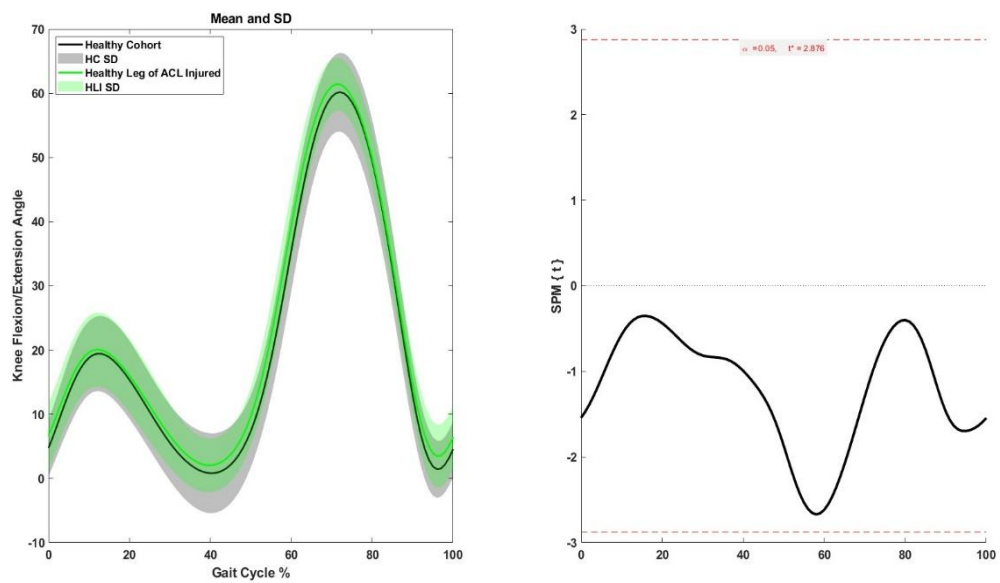


Figure 56: Independent T-test Assessing Differences in Knee Flexion Angle of the Healthy leg of ACL Injured Vs Healthy Control Subjects

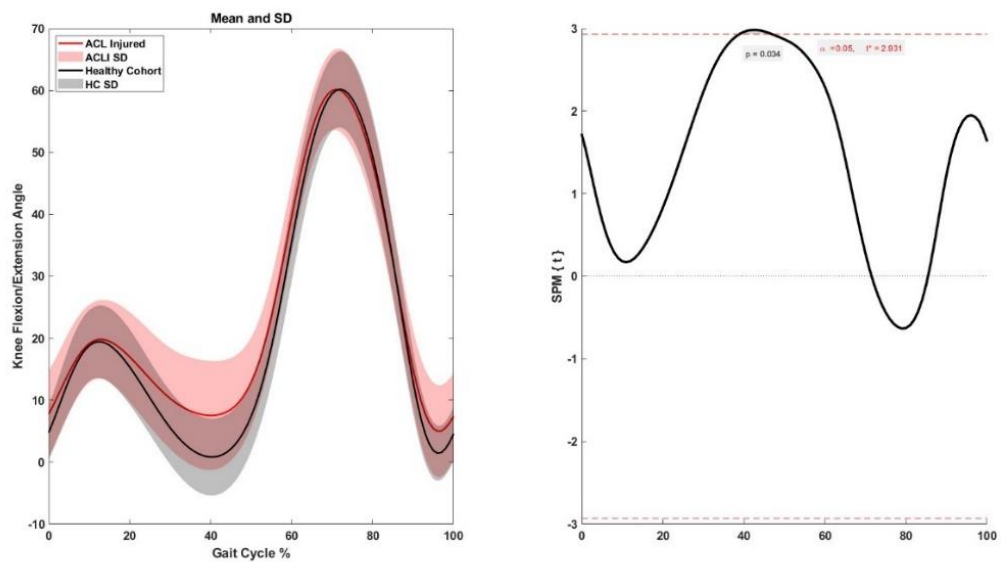


Figure 57: Independent T-test Assessing Differences in Knee Flexion Angle of the ACL Injured Vs The Healthy Control Cohort

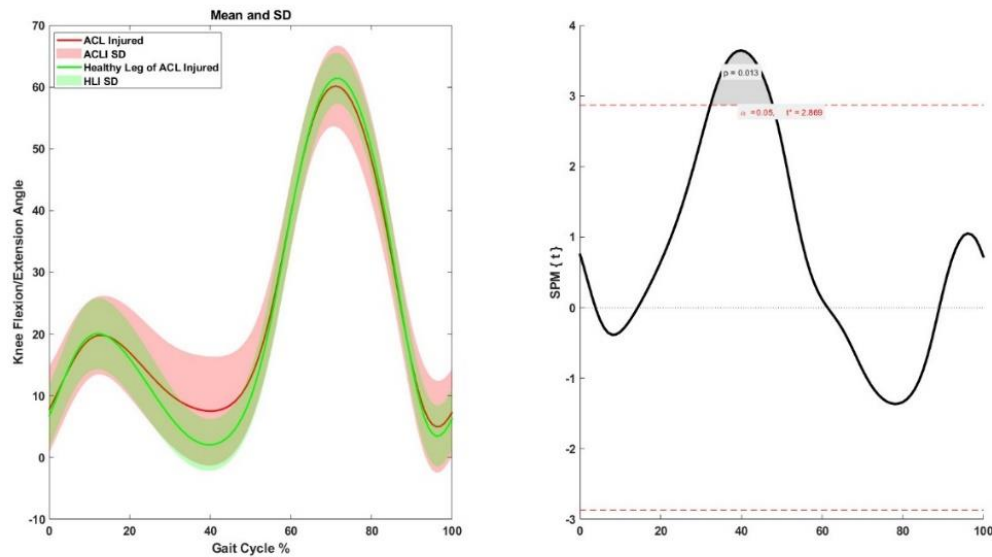


Figure 58: Independent T-test Assessing Differences in Knee Flexion Angle of ACL Injured Vs Healthy leg of ACL Injured

8.3.2 Kinematic Variations Within the Frontal Plane

An ANOVA was run comparing the frontal plane kinematics between cohorts [Figure 60]. No statistical differences were found in the gait cycle, indeed differences between cohorts did not change more than 2 degrees at any one point. Subsequently, no further t-tests were conducted.

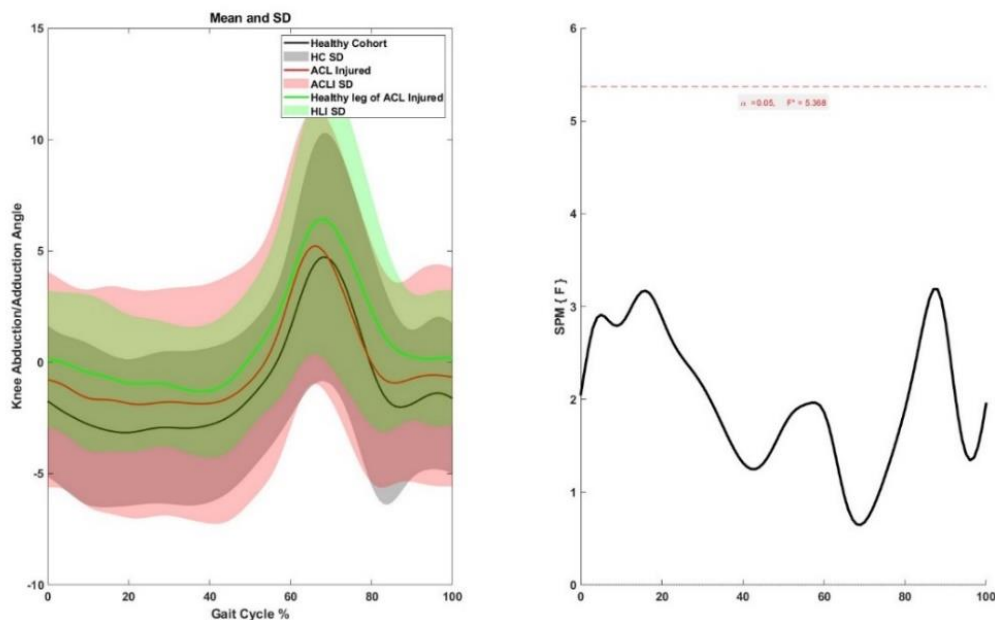


Figure 59: ANOVA to Analyse Variance of Abduction/Adduction Angle Between ACL Injured, Healthy leg of ACL injured and Healthy Control Subjects

8.3.3 Kinematic Variations Within the Axial Plane

An ANOVA and independent t-tests were used to evaluate variance between the cohorts to look at the kinematic differences in the axial plane to evaluate internal/external rotation. Statistically significant differences were observed at heel strike ($p=0.049$) between the 3 cohorts [Figure 60].

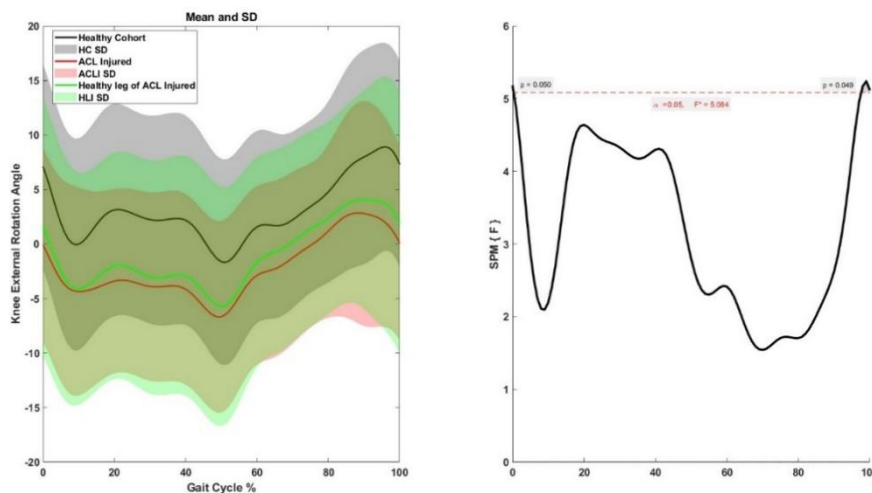


Figure 60: ANOVA to Analyse Variance of External/Internal Rotation Angle Between ACL Injured, Healthy Leg of ACL injured and Healthy Control Subjects

Independent T tests identified differences in the ACL injured compared to the healthy control subjects at heel strike ($p=0.047$), the end of the mid stance phase at approximately 15-25% of the gait cycle ($p=0.039$) and the end of the toe-off phase at approximately 40-45% of the gait cycle ($p=0.047$) [Figure 61]. Whilst the patterns of change within the axial plane remained the same within the groups, the ACL injured population exhibited more internal rotation throughout the gait cycle than the HLI and healthy control subjects. The ACL injured population only came into external rotation in the last 20% of the gait cycle. The healthy control subjects started in 7 degrees of external rotation in comparison to the ACL injured who started at 0 degrees.

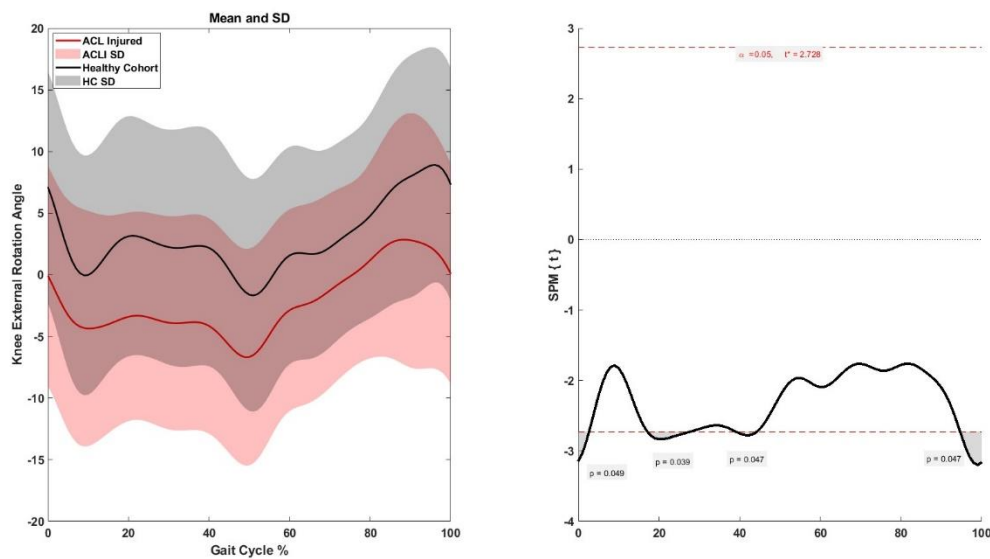


Figure 61: Independent T-Test to Analyse Differences of External/Internal Rotation Angle Between ACL Injured and Healthy Control Subjects

There were no statistically significant differences observed from the independent T-tests between the healthy leg of the injured and the ACL injured subjects [Figure 62]; or the Healthy leg of the ACL Injured and Healthy Control Subjects [Figure 63].

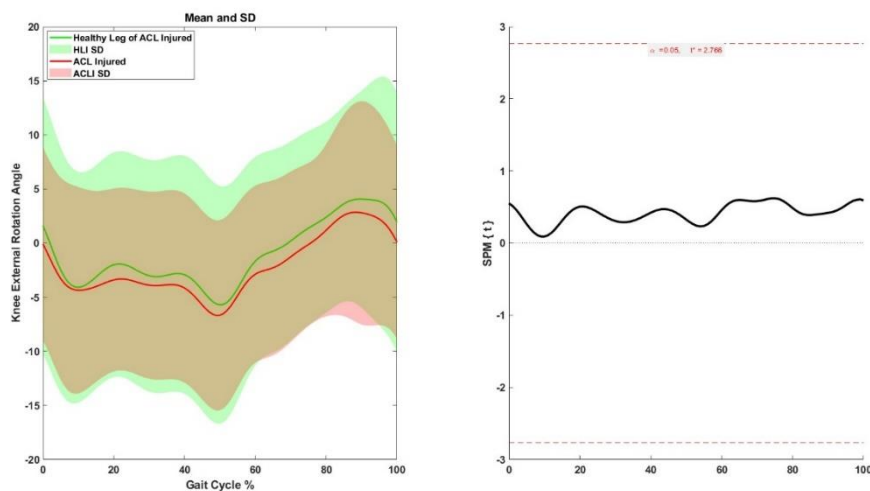


Figure 62: Independent T-Test to Analyse Differences of External/Internal Rotation Angle Between Healthy leg of the ACL Injured and ACL Injured Subjects

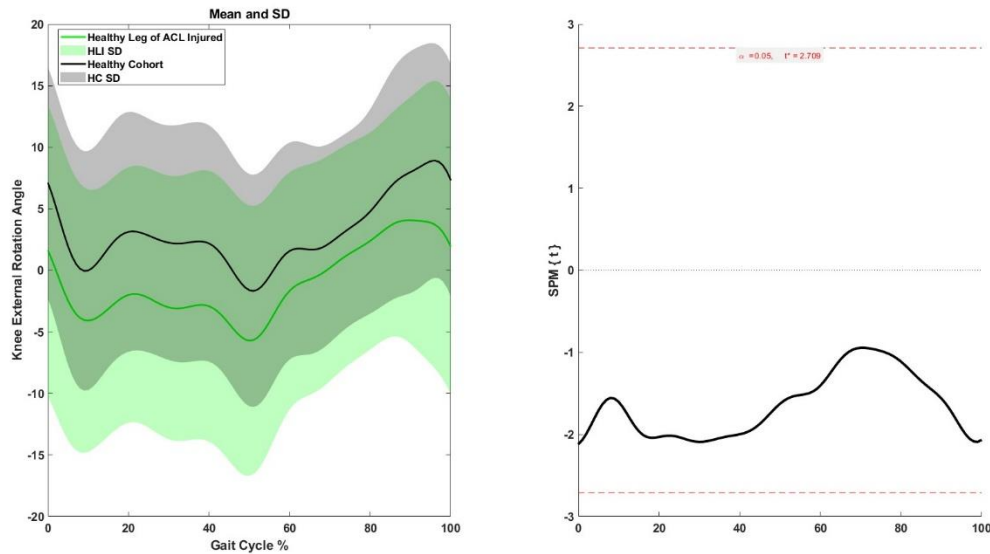


Figure 63: Independent T-Test to Analyse Differences of External/Internal Rotation Angle Between Healthy leg of the ACL Injured and Healthy Control Subjects

8.3.4 Kinematic Variations Acute VS Chronic Patients

Further comparisons of gait were conducted between acute ACL injuries (<12 weeks) (n=14) and chronic (≥ 12 weeks) (n=11). Independent T-tests were run for each plane of movement to assess the variability between the two cohorts. No significant differences were found between the acute and chronically injured cohorts within any of the 3 kinematic planes.

Although differences were not statistically significant ($p < 0.05$), some variations were observed between cohorts. Within the sagittal plane, the acutely injured cohort tended to present with higher degrees of knee flexion throughout the weight bearing stages of gait in comparison to the chronically injured. In contrast during the swing phase the chronically injured cohort tended to have higher degrees of flexion when clearing the leg off the floor [Figure 64]. The frontal plane kinematics remained very similar between cohorts [Figure 65]. When analysing the axial plane kinematics, the acutely injured cohort appeared to present with greater internal rotation during the whole gait cycle [Figure 66].

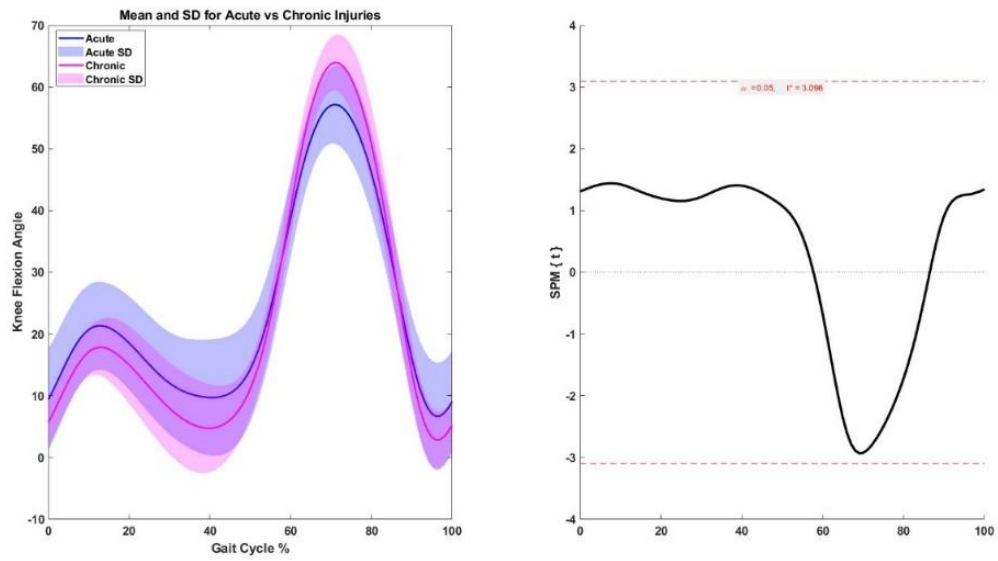


Figure 64: Independent T-test Assessing Differences in Knee Flexion Angle of Acutely Vs Chronically Injured ACL Participants

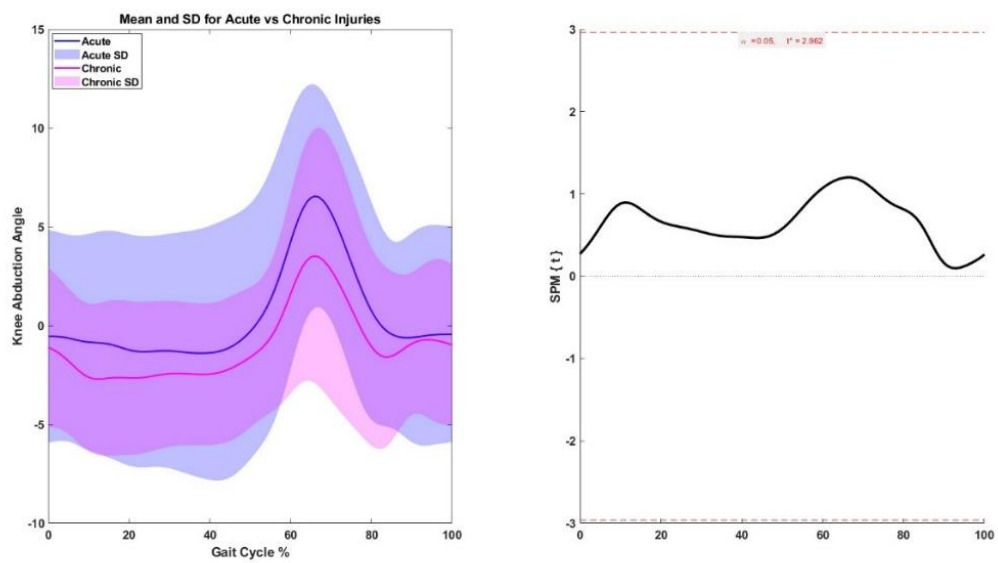


Figure 65: Independent T-test Assessing Differences in Knee Abduction Angle of Acutely Vs Chronically Injured ACL Participants

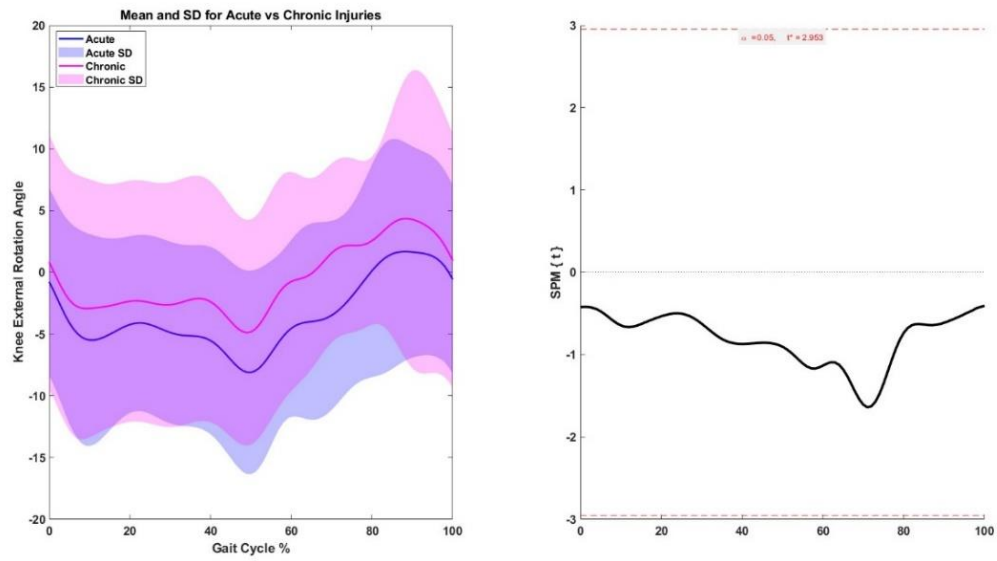


Figure 66: Independent T-test Assessing Differences in Knee External Rotation Angle of Acutely Vs Chronically Injured ACL Participants

8.4 Discussion

Gait analysis provides insights into the functional implications of ACL injuries. Understanding the alterations in gait mechanics was important in evaluating how the kinematic data from this study aligned with published literature. By examining gait kinematics, we aimed to understand the compensatory mechanisms and their impact on knee joint function in ACL-injured patients. Additionally, we sought to identify potential diagnostic indicators through functional gait assessment that could enhance the overall clinical evaluation.

The results of this study reflect the published literature on gait differences in the ACL injured group compared to healthy cohorts; Shabani et al found that ACL injured patients walked with significantly less knee extension ($13.2^{\circ} \pm 2.1^{\circ}$) throughout the stance phase duration in comparison to the healthy control group ($7.3^{\circ} \pm 2.7^{\circ}$)(226). Fuentes et al also found that ACL injured patients showed significantly higher knee flexion angles in comparison to the control group when the affected leg was loaded in the terminal stance phase or toe-off phase in the gait cycle ($P=0.024$)(118). These findings also agreed with those of Hurd et al, who found higher peak knee flexion angles in the weight bearing stance of gait along with increased hamstring activity and reduced soleus activity in the injured limb (121). All of this supports the phenomenon known as the 'pivot-shift avoidance gait' (118), injured participants within this study showed significant differences within the knee flexion angle during mid-stance and toe-off phases of gait. As postulated in previous research, this functional compensatory strategy allows for the prevention of anterolateral tibiofemoral stability (118). The same study stated that this strategy was not as pronounced in higher walking speeds, unfortunately different walking speeds were not tested within this protocol, but further research should investigate this. Overall, the consistency of these findings with previous research reinforces the reliability of the kinematic analysis conducted in this study and supports the validity of using functional gait assessment as a diagnostic tool for ACL injuries.

The pivot shift avoidance gait goes against the theory of the quadriceps avoidance gait, proposed in 1990 (229). The quadriceps avoidance gait is the phenomenon whereby biomechanics of the knee are altered to minimise the use of the quadriceps muscle and reduce strain on the knee joint. This compensatory mechanism leads to changes in the knee angle throughout the gait cycle, specifically during the stance phase where the leg remains in a more extended position.

Within the axial plane, more internal rotation was seen in the ACL injured in comparison to the other two control groups [Figure 60]. Statistically significant differences were observed from the independent T-test comparing the ACL injured against the healthy cohort. These differences were observed at heel strike ($p=0.047$), the end of the mid stance ($p=0.039$) and the end of toe off phase ($p=0.047$), all these phases were when the affected leg was in a weight bearing state, suggesting that an increased load on the leg caused compensatory mechanisms to occur. Increased internal rotation of the tibia was also supported by Shabani et al, where a significant difference ($P<0.05$) was found in the terminal stance phase ($-1.4^{\circ} \pm 0.2^{\circ}$ and $0.2^{\circ} \pm 0.3^{\circ}$ for ACL injured and control group, respectively)(226). These findings were agreed by Ren et al, who also showed increased internal rotation in terminal stance phase only (230). However, Fuentes et al, found that the mean and maximum internal rotation during the terminal stance phase was smaller in the ACLD group in comparison to the healthy controls across multiple walking speeds(118). Whilst optical motion capture systems were employed across all studies, methodology varied such as: marker placement, gait walking speeds, time from injury and additional concomitant injuries, these are all factors that need to be considered when drawing comparisons between studies (226).

The results from study found the phase at which the ACL injured participants seem to increase the tibial internal rotation is when the knee is near terminal extension. The ACLs primary role is to restrain AP tibial translation, with a secondary role of preventing excessive internal tibial rotation (119). The participants in this study seem to simultaneously increase the flexion angle and internally rotate the knee, this occurs as the ACL elongates during terminal extension(231). Whilst participants appeared to adopt the compensatory strategy to avoid terminal extension by weight-bearing on a more flexed knee, the demand of the ACL is greater when the knee is loaded meaning an increased strain to the ACL and surrounding structures (89).

The differences within the HCL leg when compared to the healthy control subjects' group were less pronounced than that of the injured cohort but still apparent in the sagittal and axial planes. The HCL differences could be due to the neuromuscular compensatory mechanisms in the injured population. No other research has published the differences of the healthy leg of the injured participant.

Despite the changes found in the sagittal and axial planes, this study showed no statistically significant differences between cohorts for the frontal plane kinematics. Other papers, including a comprehensive systematic review that have investigated this agreed with these findings (1, 4).

In the absence of the ACL, other contractile structures attempt to provide support to the knee to prevent excessive displacement (118, 232). The secondary stabilisers, such as the hamstrings, are recruited to assist in the static and dynamic stabilisation of the knee, however near terminal extension these muscle groups are less effective making it harder for the patient to compensate for the lack of stability (118). With the structural integrity of the knee compromised and the presence of effusion and pain, the large muscle groups around the knee can waste (118), the reduction in compensatory neuromuscular control of the hamstrings may be a contributing factor to the excessive tibial internal rotation observed in this study. EMG signals were investigated during laxity assessment, however measuring EMG signals during gait were beyond the scope of this work, however future work should investigate the effect of EMG signals during walking on the kinematic outputs by OMC systems.

There has been limited research investigating the differences between the acute and chronically injured patient. It is thought that whilst acute injuries exhibit an antalgic gait, more chronic injuries show an arthritic gait pattern (233). Many papers have alluded to the fact that biomechanical adaption in ACL deficient patients is time dependent (118, 234). In this analysis, a threshold of 3 months was chosen to distinguish between acute and chronic injuries, based on the understanding that significant neuromuscular adaptations and compensatory mechanisms typically begin to develop within this timeframe (121) (235). Additionally, this separation was intended to explore how the duration of injury influences gait mechanics, which could have implications for both early and long-term rehabilitation strategies. While there is some discrepancy in defining the exact periods of acute, sub-acute, and chronic phases of ACL injuries, the 3-month mark provided a balanced division of the dataset and aligns with clinical observations of the onset of chronic adaptations.

Differences were more pronounced in the acutely injured cohort within the sagittal and axial plane kinematics than their chronically injured comparators. This is not surprising given the expected increased neuromuscular control and compensatory improvements as patient's healing process progresses (236). The results from this study would suggest that generally

ACL patients exhibit higher knee flexion angles especially within the terminal stance phase of gait, this however is pronounced in the acutely injured cohort. One paper evaluated the kinematic differences using two-camera optical electrical digitiser system between acutely and chronically injured ACL deficient patients 25 years ago, they found the terminal extension knee angle was $8+/-5^{\circ}$ and $2+/-3^{\circ}$ respectively (237), agreeing with the conclusions of this study that knee angles in the sagittal plane are more flexed in the acutely injured patient.

The findings from this study also showed the acutely injured cohort to have lower knee flexion angles during the swing phase of gait, the reluctance to fully flex and extend in the acutely injured cohort may be attributable to pain and effusion, both factors tend to resolve with time(237), thus explaining a reduced effect in the chronically injured cohort.

8.5 Limitations

The gait analysis conducted in this study, while insightful, encountered limitations that must be acknowledged to fully appreciate the context and applicability of the findings. The laboratory setup only allowed for a gait analysis of approximately six strides per participant. This limited stride count may not adequately represent a patient's gait over longer distances where variables such as fatigue and stride variability become more pronounced. Longer walking tests could reveal additional differences in gait mechanics and potentially highlight fatigue-induced deviations that are not apparent in shorter tests. Participants were instructed to walk at a comfortable speed, which was not quantitatively controlled or standardised across individuals. This lack of control introduces variability in walking speeds, which can significantly affect gait dynamics. However, instructing participants to walk at their own comfortable pace does have benefits. It allows for the assessment of natural, real-world gait patterns, which can be more reflective of everyday functional mobility. This approach captures how patients might naturally compensate for their injury in daily life, providing valuable insights into their habitual movement patterns. Variations in speed can alter the biomechanical loading patterns on the knee, potentially affecting the generalisability of the findings to different walking conditions. Further work should repeat this protocol, exposing the participants to different walking speeds.

Soft tissue artefact movement is of concern with any optical motion capture, we tried to minimise the effect of this by ensuring individual markers were attached to bony prominences

rather than on any fatty tissue, in addition the aim of the assessment rig was to reduce this factor. The analysis was conducted on a flat surface without variations in incline or decline, which do not fully simulate real-world conditions that individuals may encounter daily. Different terrains can affect the biomechanical forces on the ACL and surrounding structures, influencing gait patterns in ways not captured in this study. Exploring gait dynamics across varied terrains could provide deeper insights into how slopes and uneven surfaces impact individuals with ACL injuries. While the study attempted to categorise injuries as acute or chronic based on a 3-month threshold, this distinction may oversimplify the continuum of healing stages and their impact on gait. More granular time frames or a longitudinal study design could provide a clearer picture of the progression of gait changes from acute to chronic stages.

8.6 Summary

This gait analysis study provides valuable insights into the biomechanical adaptations associated with ACL injuries, emphasising the pivotal role of compensatory gait mechanisms in managing knee stability post-injury. Our findings demonstrate that ACL-injured participants adopt a pivot-shift avoidance gait to mitigate the risk of knee subluxation and its painful consequences, such as microtrauma and potential secondary injuries to meniscal and osteochondral structures. This adaptation is characterised by a reluctance to fully extend the knee in the terminal phases of gait, likely to reduce the strain on the ACL and surrounding tissues. ACL-deficient knees showed increased internal rotation and flexion during the terminal stance phase, suggesting that the absence of ACL function prompts the knee to rely more heavily on other structures, such as the hamstrings, for stability. However, these muscles are less effective in terminal extension, underlining the importance of comprehensive rehabilitation strategies to strengthen these supporting muscle groups and restore functional stability.

The comparison of acutely versus chronically injured patients highlighted that biomechanical adaptations could evolve over time. Acutely injured patients exhibited more pronounced deviations from normal gait patterns, suggesting that early intervention could be crucial in preventing long-term functional deficits and facilitating a return to pre-injury levels of activity.

In conclusion, this study advances our understanding of the complex dynamics of ACL-deficient gait and highlights the critical need for personalised assessment and enhancement of diagnostic strategies. By demonstrating that gait analysis can reveal key compensatory mechanisms and biomechanical adaptations, our findings support the integration of gait assessment into the diagnostic process for identifying ACL tears. By improving our knowledge of how gait adaptations correlate with injury severity and recovery stages, we can enhance ACL injury management and optimise outcomes for affected individuals.

9 Cohort Study: The Use of Wearables in ACL Diagnosis

9.1 Introducing Wearables and Their Uses

As introduced in chapter 4, wearable sensors are increasingly used to track and assess biomechanics (238). Inertial Measurement Units (IMUs) are a sub-type of wearable sensors that can be used to calculate relative changes in position (239, 240); they quantify movement by providing data on acceleration, angular velocity, and rotation, they are derived from 3 components: an accelerometer, a magnetometer, and a gyroscope.

IMUs are an integral part of most technologies; mobile phones, smart watches, and navigation devices all rely on these sensors to provide aspect of their functionality. IMU are wireless, unobtrusive and highly portable which permits the continuous analysis of dynamic, full-body movement which is not confined to a laboratory setting in contrast to standard optical motion capture systems (238). This makes them uniquely equipped to measure features of knee biomechanics within the clinical setting, improving on the currently subjectively measured assessments of knee laxity (12, 64, 69, 98, 174, 179, 180, 238, 241, 242).

Recent research on measuring knee instability using inertial measurement units (IMUs) has predominantly concentrated on the pivot shift test, typically performed while the patient is under anaesthesia on the operating table (243-245). This test's subluxation-relocation mechanism allows for straightforward feature analysis by the IMU's accelerometer and gyroscope (142). However, there is significantly less quantification available for the anterior drawer and Lachman tests, which are more commonly performed in emergency departments. Integrating IMUs into these tests could enhance diagnostic accuracy in assessing knee integrity. Despite the promising potential of wearable technology to quantify joint laxity and assist in diagnosing ACL tears, this application remains underexplored. The objective of this project is to evaluate the use of IMUs as a diagnostic tool for assessing knee ligament integrity. This tool aims to identify markers or surrogate markers of joint laxity that could indicate ACL tears, ultimately improving both the speed and accuracy of diagnoses in acute settings and facilitating earlier referrals to appropriate management strategies.

As wearable sensors generate vast amounts of biomechanical data, machine learning techniques have become increasingly important in analysing this data to extract meaningful insights. Machine learning algorithms can process complex and multidimensional data sets,

identifying patterns and markers that may not be evident through traditional analysis methods. In the context of ACL injury detection, machine learning models can be trained to recognise specific movement patterns or deviations that are indicative of joint laxity or ligament damage, thereby enhancing the diagnostic capability of IMUs (237-239).

This chapter explores the use of wearable sensors to detect ACL injuries through a machine learning approach.

Research Question

Can a machine learning model distinguish between ACL injured and Healthy control patients using IMU sensor data from clinical laxity tests?

9.2 Methods

Details regarding setup, IMU placement and marker placement, and inclusion/exclusion criteria are outlined in chapter 5. This protocol was consistently applied to all participants. The IMU data was timestamped and segmented to the OMC data. This segmented data was used as the input to the machine learning model developed in this chapter.

For the development of the machine learning model, only the IMU recordings from the anterior drawer and Lachman tests were used. While additional data from other clinical tests and functional movements could further enhance this model, such extensions were beyond the scope of this project. A machine learning approach for this data was used, collaboration with other departments were required. I completed the data collection, ensuring high-quality biomechanical data from wearable sensors. Dr. Metin Bicer built the model using custom Python scripts, drawing upon his technical expertise in machine learning (246). During which, I provided clinical insights to guide its development. I was actively involved in refining the model through an iterative process, offering feedback to enhance its clinical relevance. After running the model, I conducted hyperparameter optimisation to maximise its accuracy. This collaborative effort resulted in a finely tuned model, validated for reliable use in diagnosing ACL injuries.

9.3 Model Architecture

The machine learning (ML) model is comprised of neural networks, it was designed to identify ACL injuries by using surrogate markers of knee laxity measured by the IMU sensors as the model inputs. Laxity is measured in mms; the gyroscope and accelerometer are detecting

changes in acceleration and angular velocity and the model is detecting feature extraction rather than getting the sensors to measure mm of laxity; henceforth surrogate measures of laxity are detected by the sensor systems.

A neural network is an artificial intelligence model inspired by the way the human brain processes information. This network processes data that is inputted into it and refines its understanding through training. The network progressively analyses intricate patterns within the data, ultimately leading to predictions, in this case of the presence or absence of an ACL injury.

Verification of the model's ability to classify participants as either ACL injured or healthy based was compared with the MRI results of the injured participants, which served as the diagnostic gold standard for diagnosis. By leveraging the IMU data as input data the ML model aims to accurately and efficiently identify biomechanical patterns recorded by the IMUs that are consistent with ACL injuries thereby enhancing the diagnostic processes.

Specifically, these inputs include linear acceleration and angular velocity measurements captured during the Anterior drawer and Lachman tests. Data are recorded along three axes (x, y, z) for both the femur and tibia using 2 sensors, providing a comprehensive dataset to analyse knee dynamics on both the injured (n=23) and healthy cohort (n=26). The number of axes used as data inputs and the specific axes chosen were not fixed; instead, these parameters were adjusted to optimise the model outputs. The combination of acceleration and angular velocity data from both the femur and tibia across multiple axes allows the model to capture the complex dynamics of the knee. By optimising which axes are included, the model can focus on the most relevant data, thereby improving its ability to accurately identify ACL injuries.

The optical motion capture data was not used within this ML model; however, this could be incorporated into further work to train the ML model to enhance its accuracy. The outputs of the model are binary classifications, indicating either the presence (1) or absence (0) of an ACL injury.

To ensure the robustness and generalisability of the machine learning model, a k-fold cross-validation strategy was employed. In each of the six folds, five-sixths (83.3%) of the subjects were used to train the model, while the remaining one-sixth (16.7%) served as the test set.

This process was repeated across all six folds, ensuring that each subset of subjects was used exactly once as the test set. The use of five-sixths for training allows the model to learn from a substantial portion of the data, increasing its exposure to diverse patterns and improving its ability to generalise to new data. The remaining one-sixth is used to test the model's performance on unseen data, providing a reliable measure of its diagnostic accuracy. This approach is particularly important in clinical contexts, where overfitting—performing well on training data but poorly on new data—can lead to inaccurate diagnoses. By cycling through all subsets of the data, k-fold cross-validation ensures a comprehensive evaluation of the model, yielding an unbiased assessment of its ability to detect ACL injuries across different data segments. This structured methodology maximises the utility of the dataset, offering robust insights into the model's performance throughout its development.

The data was segmented based on each repetition of the clinical test performed. A single passive pull on the limb to induce laxity was considered one repetition of the relative test. This segmentation was achieved by aligning the IMU data with the Optical Motion Capture (OMC) data, where the start and end of each repetition were visually identifiable. To address the variability in the length of repetitions, each was normalised to a consistent range of 0-100%. This preprocessing step ensured uniformity across the data, facilitating more accurate and consistent analysis in subsequent stages.

Given that each IMU sensor provided six time-series, across 3 axes by 2 sensors, the data forming a repetition was comprised of a 12x101 matrix. Two approaches were explored: One used the data from the clinical tests in each individual legs, looking at each leg of the participant in isolation. Another worked by analysing the sensor data differences between legs in the same patient. Data from both injured and healthy cohorts were used in both methodologies. Both methodologies used the whole data set to build the model, multiple reps from both clinical tests for all participants were used for both the tibial and femoral IMU.

9.3.1 Method 1 Sensor Interaction

The first approach, termed Individual Leg Analysis, employs a dual neural network architecture [Figure 67]. One network process raw IMU data from each leg independently, while the other incorporates contextual leg-side information (right or left). This method does not analyse side-to-side differences within participants but aims to understand the dynamics of each leg on its own. By incorporating leg-side information, the model accounts for potential

lateralisation effects which are apparent in right or left knees with respect to knee dynamics, which can be critical for identifying differences in injury patterns specific to the injured or non-injured side.

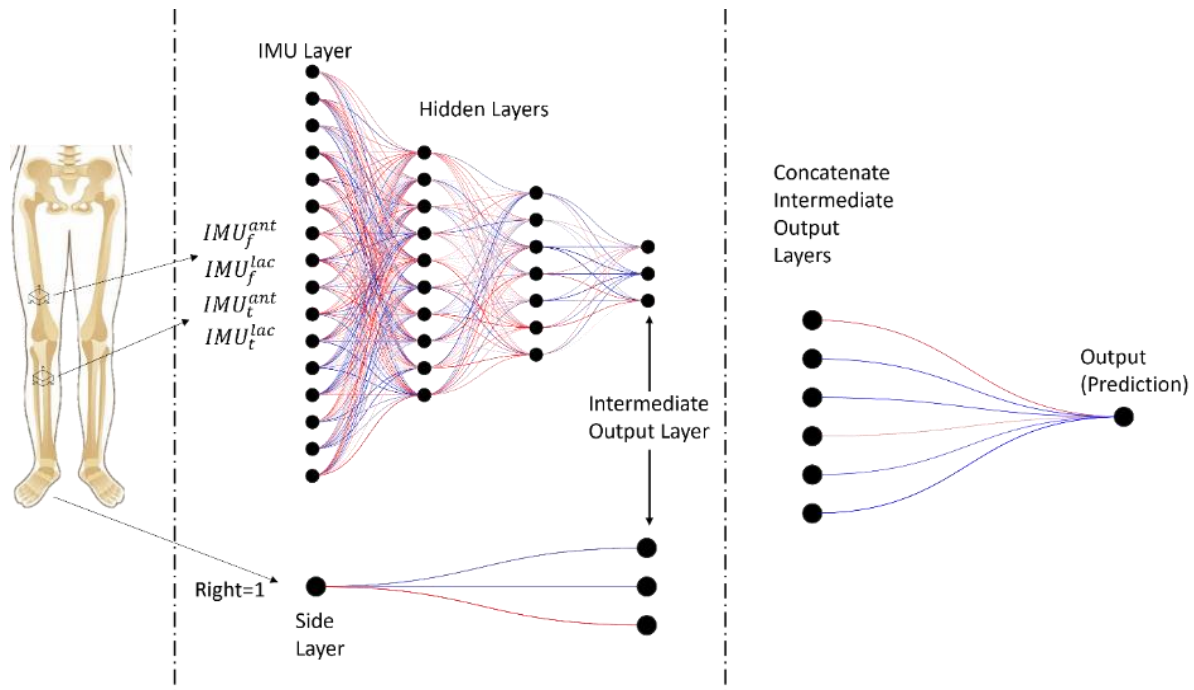


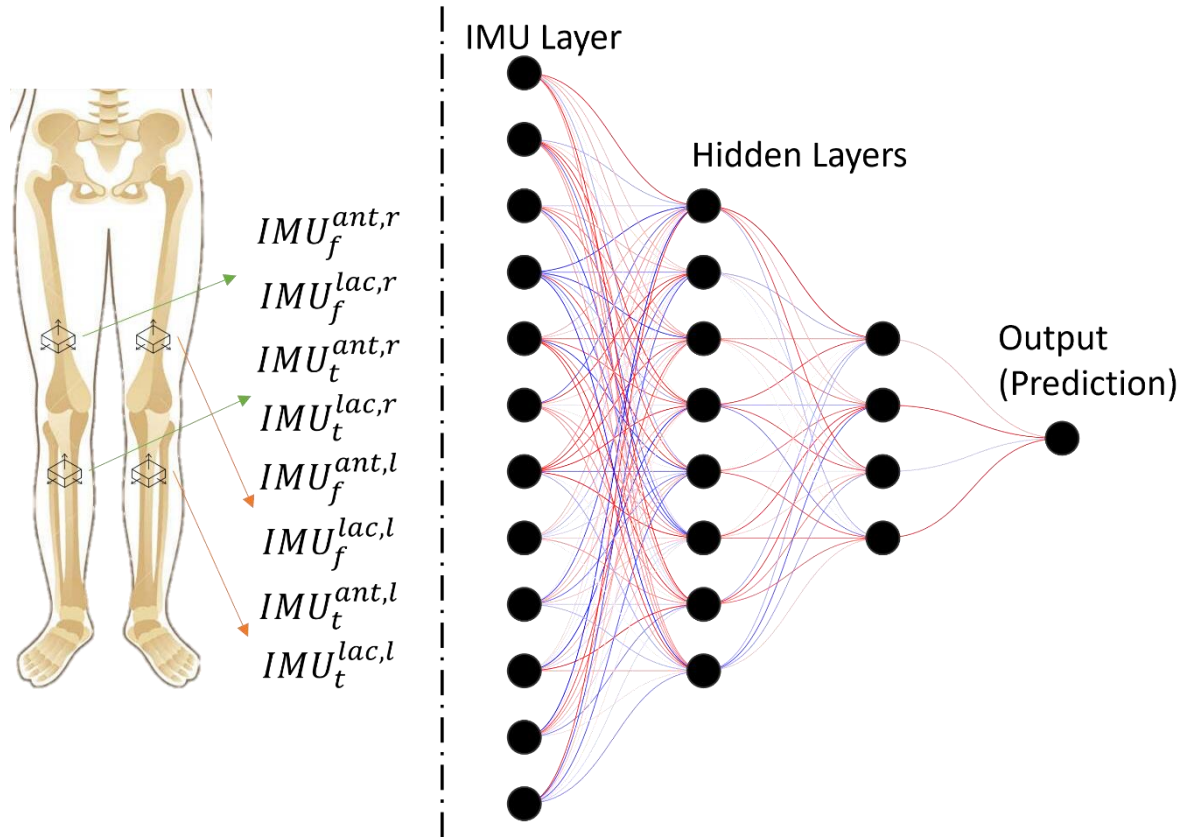
Figure 67: Representing the neural network of methodology 1. The first approach to process the inertial measurement unit data to predict ACL injuries. Each black circle is a neuron of the neural network model. Blue and red lines are the network parameters.

**** IMU_f^{ant} – Femoral IMU during Anterior drawer test, IMU_f^{lach} – Femoral IMU during Lachman test, IMU_t^{ant} – Tibial IMU during Anterior drawer test, IMU_t^{lach} – Tibial IMU during Lachman test****

9.3.2 Method 2 Sensor Interaction

The second approach; a Comparative Leg Analysis, integrates IMU data from both legs for each repetition to capture potential inter-leg differences and interactions (this compares the differences between R vs L leg for the respective patient). This method results in a single neural network model that processes this combined dataset to predict ACL injuries [Figure 68]. By leveraging comparisons between the injured and non-injured leg (or between both legs if both are injured or healthy), this approach provides a more comprehensive perspective on knee dynamics, potentially enhancing the model's ability to detect ACL injuries through the interplay of data from both legs.

Figure 68: Figure representing the neural network of methodology 2. The second approach to process the inertial measurement unit data to predict ACL injuries. Each black circle is a neuron of the neural network model. Blue and red lines are the network parameters that are optimised to classify ACL injuries accurately.



****** IMU_f^{ant} – Femoral IMU during Anterior drawer test, IMU_f^{lach} – Femoral IMU during Lachman test, IMU_t^{ant} – Tibial IMU during Anterior drawer test, IMU_t^{lach} – Tibial IMU during Lachman test******

9.3.3 Model Accuracy and Refinement

The model's accuracy is determined by the diagnostic performance characteristics: accuracy, sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV). These are explained and broken down earlier in the thesis in chapter 2.7. Accuracy, as a fundamental metric, determined the overall correctness of the model's predictions. Collectively, these metrics allow the model's performance to be assessed in the context of detecting ACL injuries.

The current study uses two methods to assess the accuracy of the ML models: one focusing on individual attempts (repetition-wise) and the other on overall performance per person (subject-wise). Repetition-wise is the accuracy value when the data is just one repetition of a clinical test performed on a given participant; subject-wise produces the accuracy when all of

the repetition data for a given participant is used. For the latter, every repetition prediction for that specific subject is tallied, and the most common outcome determines the subject's final classification. This approach aims to offer a comprehensive assessment by averaging the model's predictions across multiple tests for each subject, thereby smoothing out any anomalies in individual test results. After setting up the methodologies for the two approaches, several experiments (neural network trainings) were run to determine the parameter settings that optimise the diagnostic outcomes of the model.

Machine learning models are comprised of hyperparameters, each have a different effect on handling the model data and subsequently the model's outputs. In both approaches, the model undergoes 'training' to optimise the accuracy of the model. The neural network has weights, these weights are determined by the hyperparameters of the model. Each hyperparameter is outlined in Appendix E. The outputs of the models are determined by a binary cross-entropy loss function, which measures the difference between the network's predictions (ACL injury =1 or Healthy control=0) and the actual outcomes. The model employed a gradient-based optimization algorithm, specifically backpropagation, to iteratively adjust the weights. Backpropagation calculates the gradient of the loss function and updates the weights to minimise this loss. This training is iterative until reaching a plateau, where further adjustments yielded negligible improvements in accuracy, ensuring the model's efficiency in detecting ACL injuries.

9.4 Results

The data was initially trained on a subset of the data (n=36). It was then trained on the entire data set once data collection was complete (n=50).

9.4.1 Method 1: 36 Subjects

In the first approach, three layers with 1024, 256 and 64 neurons were used in the neural network responsible for processing the input IMU data. A single layer with 64 neurons was used for both neural networks processing the leg-side information and intermediate layer. The evaluation metrics were optimised when using all components of the IMU data (linear acceleration and angular velocity in all axes). This resulted in 76% accuracy in classifying repetitions, while subjects were classified with an accuracy of 83%. Although the subject-wise

accuracy was satisfactory, the sensitivity and PPV were calculated as 59% and 67%, respectively, meaning that just 59% of the actual ACL injury cases could be captured.

9.4.2 Method 2: 36 Subjects

The second approach greatly improved the performance of subject-wise predictions with accuracy, sensitivity, specificity, PPV and NPV of 85%, 82%, 88%, 88% and 83%, respectively. This performance was obtained using a 2-layered neural network with 256 and 16 neurons [Figure 68] by processing just two components of the IMU data corresponding to the angular velocity in flexion-extension axis.

9.4.3 Method 2: 50 Subjects

The same parameters used to obtain 85% accuracy on the model which was trained and tested on 36 subjects were then used on the whole data set (n=50), this decreased diagnostic accuracy to 62% when trying to identify participants as being ACL injured or healthy. Indicating the model is not generalisable to a wider population and potentially was overfitted to the partial data set (n=30).

For this reason, parameters were adjusted to optimise diagnostic performance characteristics for the whole data set. A model was built on top of the machine learning model which iteratively explored multiple parameter combinations and adjustments, this allowed for the optimal parameter settings to be identified efficiently [

Table 56]. Diagnostic performance characteristic outputs produced by these parameter settings can be found in Table 55.

9.4.4 ROC Curve Analysis and Model Performance

The machine learning model's diagnostic performance was evaluated using Receiver Operating Characteristic (ROC) analysis. The ROC curve (Figure 69) yielded an Area Under the ROC Curve (AUROC) of 0.77, indicating that the model demonstrates a reasonable ability to distinguish between ACL-injured and healthy participants based on wearable sensor data. The AUROC score suggests moderate to good diagnostic capability, highlighting that the model can correctly rank participants by their likelihood of having an ACL injury most of the time.

In addition to ROC analysis, the model's F1 score was computed, achieving 0.67. This score balances both precision and recall, making it an important metric for evaluating performance, particularly in clinical settings where both false positives and false negatives carry significant implications. These results complement the diagnostic accuracy of 71%, showing consistency across multiple performance measures.

Table 55: Diagnostic performance characteristics for optimal parameter settings for identifying ACL injured and healthy control subjects for both identifying individual repetitions and participants as a whole.

Diagnostic Performance Characteristic	Repetitions (%)	Participants (%)
Accuracy	71	71
Sensitivity	61	62
PPV	75	79
Specificity	49	75
NPV	83	68

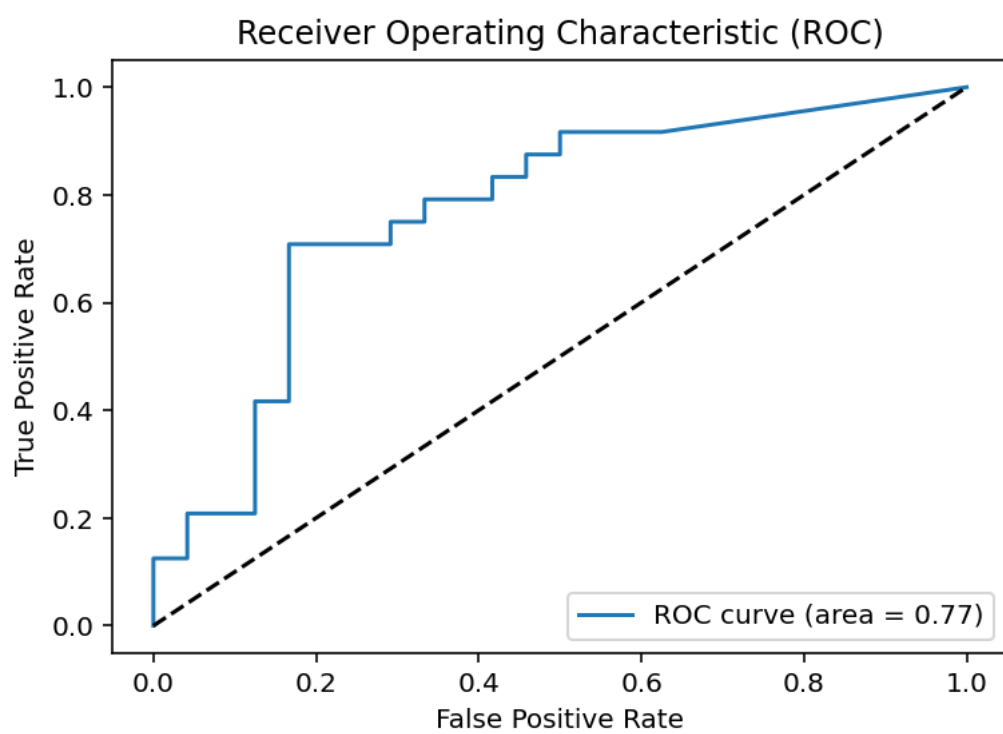


Figure 69: Receiver Operating Characteristic (ROC) Curve for Participant-Level Predictions. The area under the curve (AUC) was 0.77, indicating moderate diagnostic accuracy.

Table 56: Parameter settings from models

	Parameters Method 1 (n=36)	Parameters Method 2 (n=36)	Parameters Method 2 (n=50)
Number of Splits	6	6	6
Down Sampling	10	10	10
Batch size	512	512	1024
Hidden sizes	1024, 256, 64	256, 16	216, 27
Drop out	0.5	0.5	0.66
Included Axes (See above axes key)	5, 11	5, 11	1, 2, 4, 5, 10, 11
Confidence level	0.2	0.2	0.49
Learning Rate	0.1	0.1	0
Step size	20	20	34
Gamma	0.1	0.1	0.9
Epochs	30	30	66
Confidence Limit Participant	52	52	58

****Included Axes Key-** The included axes determine the data inputted into the model. This model includes 2 sensors, each have an X, Y and Z axis across an accelerometer and gyroscope.

corresponds to the associated axes of the respective sensor:

The following are the axes codes for each trial.

- 0,1,2 -> acc femur (x,y,z)
- 3,4,5 -> gyro femur (x,y,z)
- 6,7,8 -> acc tibia (x,y,z)
- 9,10,11 -> gyro tibia (x,y,z)**

9.5 Discussion

The diagnostic challenges which accompany ACL injuries are attributable to the variability within the interpretation of joint assessment, this impacts healthcare delivery across the care pathway (38, 64, 69). This work highlights the potential for deploying wearable devices and

ML models to facilitate the diagnostic process. Wearables could serve as a clinical assessment aid, providing clinicians with guidance on the presence of injuries, thereby enhancing certainty in decision-making.

The ML model developed in this study aims to refine the diagnostic process by identifying patients more likely to have an ACL tear based on biomechanical data captured via IMUs during physical tests like the Lachman and Anterior drawer tests. While the model achieved a diagnostic accuracy of 71%—a result that is only marginally better than the diagnostic capabilities of Lachmeter or VICON systems—it offers distinct advantages in portability, cost-effectiveness, and non-intrusiveness. Wearables, unlike these other methods, provide flexibility for assessing knee dynamics in multiplanar movements outside a laboratory setting, enhancing their suitability for real-world clinical environments.

It is important to recognize that this 71% accuracy was achieved with an initial, relatively small wearable data subset; with expanded data input and increased model sophistication, there is strong potential for significantly improved accuracy. Enhancing model complexity and training on a larger dataset could refine the diagnostic capabilities of wearables, aligning them more closely with clinical demands and increasing their utility in healthcare pathways. These advantages make wearables a promising tool in triage, potentially reducing unnecessary imaging, streamlining workflows, and enabling more effective allocation of specialist resources.

The ROC curve analysis demonstrated an area under the curve (AUROC) of 0.77, indicating moderate diagnostic performance for distinguishing ACL-injured participants from healthy participants using wearable sensor data. This result suggests that the model performs above random chance but still leaves room for optimisation. Additionally, the F1 score of 0.67 reflects a reasonable balance between sensitivity and precision in the model's classifications. These findings align with the performance levels observed in traditional clinical methods such as manual Lachman or Anterior Drawer tests, where diagnostic accuracy can vary depending on clinician experience. The advantage of this model lies in providing objective, sensor-driven assessments that reduce subjectivity and operator dependency.

The model's confidence parameters were instrumental in determining final participant-level predictions. The confidence level threshold set for trial classification ensures that individual

repetitions are assessed consistently. However, the confidence limit threshold of 58% at the participant level likely increased specificity by requiring a majority of positive trials to establish an injured classification. This threshold may have contributed to a moderate sensitivity and balanced specificity, as seen in the ROC curve. The balance reflected in the F1 score is crucial in clinical contexts, where both false positives and false negatives can have significant consequences. Reducing false positives can prevent unnecessary interventions, while improving sensitivity can ensure timely identification of ACL injuries. The model's current performance demonstrates potential for use as a supplementary diagnostic tool to enhance clinical decision-making.

Wearables have already proven useful in performance optimisation and tracking systems worldwide, providing valuable bioinformatics for various applications (14). The tri-axial high sampling rate, including an accelerometer and gyroscope, allows for accurate and sensitive data capture of intricate joint movements. The proposed system would function as a wearable device, with sensors mounted onto a knee sleeve worn during clinical exams. An attached interface would process the data and run the ML model, offering real-time diagnostic support directly in the clinical setting. This integration into routine clinical workflows would allow for timely and accurate assessments, providing a more efficient alternative to current practices that often rely on imaging and subjective clinical judgement.

Automatic hyperparameter optimisation was used in this methodology to offer a computationally efficient method of retrieving high diagnostic accuracy outputs. It offers a structured methodology to efficiently iterate through parameter settings which ensures that models not only achieve high accuracy but are also computationally feasible to deploy in clinical environments. The tuning of hyperparameters such as learning rate, batch size, and model architecture, directly influences the model's ability to learn from data without overfitting or underfitting.

In this project, specific parameters such as the number of layers and the dropout rate were carefully adjusted, drawing on established practices in the field of machine learning, which have shown how crucial these settings are for the success of healthcare applications (247, 248). Although we conducted extensive hyperparameter optimisation, the computational and time demands inherent in exploring all possible combinations meant that further work is

necessary (247). Future research will need to investigate additional combinations and more sophisticated optimisation techniques to fully realise the potential of the model.

Parameter refinement is just one of the ways to improve and optimise ML model accuracy, increasing the amount and diversity of data inputs allows a model to learn from a broader dataset, adding depth and complexity. Incorporating patients' subjective history data, such as details of their symptoms and mechanism of injury may provide valuable context to enhance the model. Other examples of additional model inputs which would enrich the data set include IMU data from gait assessments, other clinical tests, and functional tasks. These inputs could enhance the model's accuracy and robustness by providing a more comprehensive view of the patient's biomechanical and clinical profile. Furthermore, the model could benefit from learning from VICON data; by training the IMU data against the biomechanical data, it enriches the data set and therefore enhancing the model's ability to detect changes within movement patterns (249) (250).

By leveraging data and technology, artificial intelligence solutions hold the potential to enhance the efficiency of care services and patient outcomes. This study is yet another example of how technology can advance health services, marking a milestone in the application of wearable technology and ML in clinical MSK diagnostics. Despite the significant potential, challenges associated with medical technology, such as data privacy, integration into clinical workflows, and initial costs, must be addressed to realise these benefits fully.

In order to overcome these challenges and implement ML solutions in clinical pathways effectively, pilot studies should be conducted to ensure seamless integration into existing workflows while addressing data privacy through strong encryption and regulatory compliance. A phased rollout can help manage costs and demonstrate the value of the technology, supported by continuous training for clinicians and technical updates. Collaborations with research institutions and regular evaluations will ensure the system's effectiveness and adaptability, enabling it to improve patient care and operational efficiency over time.

ML solutions are already being implemented at various points within clinical pathways across multiple medical disciplines. Their utility expanding to enhancing the clinical decision making within emergency department workflows(238, 239), improving the prediction of mortality

rates for post cardiac surgery, and facilitating skin cancer diagnoses (251). Furthermore, the role of ML in analysing MRI scans has been explored in some depth, whilst not directly comparable to this study, it provides a valuable reference point. Deep learning models have been shown to perform at levels comparable to, or better than, trained radiologists in diagnosing ACL tears from MRI images, achieving high sensitivity and specificity (240, 241, 252). These findings highlight the broader applicability of ML in musculoskeletal diagnostics and suggest potential areas for future integration.

The development and integration of ML models into ACL diagnostics could signify a transformative step towards more precise and efficient triage, with potential applications extending to other clinical areas beyond this (238, 239). For example, the model's use of IMU sensor data to detect ACL injuries via a binary loss entropy function offers a strong foundation for broader clinical applications. By capturing detailed biomechanical markers, the model can enhance early diagnosis, identifying subtle joint instability that might not yet manifest as a full injury, which is particularly useful in preventive care. The model's ability to process real-time data could also be adapted for continuous monitoring during rehabilitation, allowing for dynamic adjustments to treatment plans and reducing the risk of re-injury.

Furthermore, the model's binary classification approach could be expanded to support differential diagnosis, distinguishing between various knee injuries, and could integrate seamlessly into existing clinical decision support systems. This makes it a versatile tool, scalable for use in remote settings where advanced imaging might be unavailable, thus aiding in preliminary diagnoses and guiding further treatment decisions. Overall, the model's adaptability highlights its potential to transform multiple stages of the clinical pathway, improving patient outcomes through precision and efficiency.

With further refinements and an expanded dataset, the ML model could extend its utility beyond initial triage to significantly impact clinical decision-making in ACL injury management. The model could help determine whether a patient would benefit more from surgical intervention or conservative treatment by analysing a broader range of factors, leading to personalised treatment recommendations. Additionally, the model could establish objective criteria for return-to-play decisions, using biomechanical markers to ensure patients are ready to resume activities safely. It could also guide rehabilitation by identifying specific

milestones that indicate when patients are ready to progress to the next stage of recovery, thereby optimising rehabilitation protocols and improving outcomes.

This study represents a significant advancement in integrating wearable technologies and ML into ACL injury diagnostics. By focusing on real-time biomechanical assessments during clinical tests, this work provides a foundation for improving the diagnostic process and therefore patient outcomes in acute settings. The innovative approach of using IMU data for ML-driven diagnostics demonstrates the potential for broader applications across various clinical domains, paving the way for more efficient and effective healthcare solutions.

9.6 Limitations

Several limitations of this machine learning model should be noted. For instance, the current study utilises a limited dataset, which may affect the generalisability of the model's findings. While the data set was trained and tested on the clinical assessment data of 100 legs, with each subject undergoing multiple repetitions resulting in over 2000 data points, this is still not a large dataset for a sophisticated AI model. The fact that we did not achieve the same (or highly similar) accuracy outputs when using the same parameters for the model trained on 36 subjects and the model trained on 50 subjects indicates potential overfitting. A larger dataset would help mitigate this issue.

The AUROC and F1 score further reflect this point. Whilst they both support the model's utility, there are several areas for improvement. The dataset size and variability may have influenced performance, particularly with regard to trial consistency and sensor noise. Expanding the dataset with more diverse participants and repetitions could enhance the model's robustness. Future iterations could explore alternative machine learning algorithms and refine feature extraction from sensor data to improve diagnostic accuracy. Additionally, recalibrating the confidence thresholds based on new data may further optimise participant-level classification performance.

Furthermore, the model is in early stages of development, it could be improved by incorporating data from other types of laxity tests that induce rotational, valgus, and varus movements; training the model to identify concomitant injuries would be beneficial as ACL injuries are often not in isolation, injuries to surrounding structures may influence the biomechanics during the clinical tests which was explored in part in chapter 6.2.5. Future

studies with larger, more diverse patient diverse populations, such as: patients with all types and variation of concomitant injury alongside ACL pathology, in addition the inclusion of injured patients that were negative for ACL ruptures but have incurred other ligamentous or meniscal damage would enhance the model's robustness and to ensure its applicability across people with knee injury.

Although Optical Motion Capture (OMC) data was collected alongside IMU data, future work could integrate this OMC data into the model, allowing the IMU sensor data to be validated and enhanced by the motion capture data. The model should also include the clinical assessment data from multiple examiners so that it is more generalisable to different types of assessors. The current parameter optimisation process, although effective, remains in its early stages. Continued refinement of model parameters is essential, particularly as new data becomes available. This iterative process is crucial for maintaining the model's accuracy and efficiency but requires substantial computational resources, which may limit rapid deployment in clinical settings.

9.7 Summary

This study represents a significant advancement in the integration of wearable technologies and machine learning (ML) into the diagnostic processes for ACL injuries. The ML model developed in this study achieved a diagnostic accuracy of 71% for ACL injuries using data from the Lachman and Anterior drawer tests. This provides an encouraging foundation for improving the triage process for ACL tears. This approach has the potential to reduce unnecessary imaging, streamline clinical workflows, and more effectively allocate medical resources. Continuation of hyperparameter optimisation as well as enriching the model by integrating more clinical data into the model's inputs will improve and build upon this AI solution. Nonetheless even in the early stages, this research has found that wearable technologies, when used alongside traditional assessments, can provide greater certainty in clinical decisions and offer valuable biofeedback, enhancing the overall diagnostic process.

10 Conclusions and Future Work

10.1 Introduction

This chapter provides a comprehensive summary of the work conducted in the thesis and brings together the main findings. This research addresses a prevalent clinical challenge through the application of technical innovation. By integrating advanced machine learning models with wearable sensor technology, this study has contributed to the development of more accurate and efficient clinical diagnostic approach for ACL injuries.

This thesis explores the clinical problem through multiple perspectives. A systematic review was conducted to analyse diagnostic timeframes and the accuracy of current diagnostic methods, providing a critical evaluation of existing practices. Clinicians' experiences were also examined by surveying their confidence in assessment, prioritisation of assessment methods, and proposed management for this patient group. This survey was essential in highlighting the practical challenges faced in clinical settings, providing real-world insights that are crucial for guiding the development of effective technological solutions. By gathering this information, the study aims to bridge the gap between theoretical innovation and practical application, ensuring that the proposed technologies are both relevant and applicable in real-world clinical environments.

Current technological practices for laxity quantification were obtained through a scoping review which helped inform the protocol and sensor data collection. Throughout the thesis, methodologies were explored, from laxity quantification and detailed gait analysis using OMC systems, EMG data to capture muscle activity, to the optimisation of a machine learning model using wearable sensor data. Each played a crucial role in enhancing the reliability and applicability of the proposed solutions. The insights gained from this research not only address challenges in diagnosing ACL injuries but also pave the way for future advancements in the use of artificial intelligence and wearable technology in clinical settings.

10.1.1 Significance of the Research:

The significance of this research lies in its potential to revolutionise the diagnostic processes for ACL injuries. By identifying key areas for improvement in the current diagnostic pathway, this research unveiled potential points for innovation and improvement setting a foundation for developing more objective clinical diagnostic protocols and helps unveil the discrepancies

within the management of ACL injuries. The biomechanical analysis conducted in this study offers a detailed understanding of knee laxity, translating subjective clinical observations into quantifiable data.

This study is novel in its use of an Optical Motion Capture (OMC) system that intricately maps knee movement, enabling segmental and multiplanar analysis during clinical tests. The model development of the assessment rig allowed for the control of soft tissue artefact movement, ensuring accurate data capture. This approach is one of the first to compare multiple clinical tests for knee laxity, providing detailed insights that could enhance diagnostic accuracy and influence clinical practices in ACL injury assessment. In addition, this research provides novel insight as to how the extent of injury changes knee laxity and confirms that the current methods of measuring laxity with arthrometers are insufficient.

The understanding and quantification of muscle guarding is the first to do so. It provides information on how patients respond by changing their muscle activation during clinical assessment and how these compensatory strategies change between injured and healthy cohorts throughout different clinical tests.

The exploration and integration of wearable sensor technology presents an advancement in the field of musculoskeletal and orthopaedic medicine. The use of IMU sensors to detect knee laxity markers provides continuous, real-time data that can significantly improve the accuracy and efficiency of ACL injury diagnostics. This innovation not only supports clinicians in making more informed decisions, but it could reduce the burden on healthcare systems by streamlining the diagnostic process. Overall, the research contributes to both the scientific understanding of knee biomechanics, and the practical application of advanced diagnostic tools, paving the way for improved patient outcomes and more sustainable healthcare practices.

10.2 Key Findings and Contributions

10.2.1 Current Clinical Practice

Inconsistencies in Diagnostic Approaches: The research highlighted significant discrepancies in the diagnostic methods employed across different clinical settings. Emergency departments and trauma centers often rely on subjectively measured laxity tests, which can vary widely based on the clinician's experience and expertise; the systematic review found

variability in diagnostic accuracy can be anywhere from 9.5-100%. This variability contributes to inconsistent diagnostic outcomes and prolonged uncertainty for patients.

Delays in Diagnosis: One of the most pressing issues identified is the delay in diagnosing ACL injuries. The systematic review indicated that the average time to reach a diagnosis is 68.6 days and as many as 5 separate appointments, these statistics are potentially optimistic as they pertain to specialist care with clear referral pathways. Separate reviews found diagnosis can take as long as 21 months when primary care is involved. Long diagnosis often results in delayed treatment and prolonged patient discomfort. This delay is heavily dependent on the pathways of the respective hospitals and is exacerbated by the reliance on clinical assessments that are ambiguous, necessitating further imaging or specialist referral. False negative diagnosis and delay to diagnosis can increase the chance of secondary or worsening of injury, which can contribute to the exacerbation of PTOA.

Impact of Swelling and Muscle Guarding: This study highlighted the complexities of assessing muscle guarding in ACL-injured patients and its effect on muscle activity in the hamstrings and gastrocnemius during clinical tests. Significant increases in muscle activity were observed among ACL-injured participants. However, no significant relationship was found between muscle guarding and anterior tibial translation (ATT), suggesting that increased muscle activity does not directly correlate with knee laxity. This lack of correlation could be due to the complexities in accurately quantifying muscle guarding or may reflect the varied nature of ACL injuries. To further explore these findings, incorporating electromyography (EMG) data into the machine learning (ML) model could provide a more comprehensive analysis by expanding the data beyond the current inertial measurement unit (IMU) inputs. While a direct link between increased EMG signals and knee laxity was not identified, injured participants did show increased muscle activity in the hamstrings and gastrocnemius. By integrating EMG data, the ML model could better identify differences in muscle activity between cohorts, potentially improving the differentiation between injured and non-injured individuals.

Reliance on Radiological Confirmation: The survey conducted in Chapter 3 supports that clinicians prioritise laxity tests within their assessment of ACL injuries. Despite this, even specialists have varying levels of confidence in their ligamentous integrity assessment. Many clinicians expressed a lack of confidence in diagnosing ACL injuries based solely on clinical examination without imaging support. These imaging techniques, though effective, are

resource-intensive and not always immediately available, contributing to further delays in the diagnostic pathway. In addition, they lack the ability to reflect patient functionality, and although they can provide information-rich data on the morphology on the knee structures, they cannot provide the crucial information of how the injured structure is performing under tension. Quantifiable data on functionality would help decrease the reliance of radiological confirmation and add valuable context of the corresponding ligament functionality on morphology reports.

10.2.2 Biomechanics

The biomechanical studies conducted as part of this research provided significant insights into the quantification of knee laxity, a critical factor in diagnosing ACL injuries. The key findings from these studies include:

Development of Biomechanical Models: Using advanced optical motion capture systems, the research successfully developed sophisticated biomechanical models that can quantify knee laxity in multiple planes of motion during clinical assessments. These models provide a detailed analysis of knee joint behaviour, capturing subtle biomechanical changes often missed in traditional assessments. The novelty of these models lies in their ability to map the articulating surfaces of the knee, allowing for laxity calculations relative to the closest bony points to the joint rather than traditional reference points like the tibial tuberosity. This precision is crucial when investigating small changes in laxity. Additionally, the models enabled multiplanar analysis, which was particularly useful in defining anteromedial rotary laxity—a capability that had previously been limited to cadaveric studies.

Validation of New Clinical Tests and Variations of Laxity Assessment: The study introduced and validated new assessment protocols that isolate movements to understand laxity in different compartments of the knee and assess concomitant injuries to ACL tears. Capturing these fine-scale movements is crucial for precise diagnosis, allowing clinicians to detect minor abnormalities that might be missed by traditional assessments. This was in both validating the benefit of the ADSEOB test as another method to assess ATT and investing the unique ability of the Feagin Thomas test to assess for AMRL. These protocols provided insights into variations of clinical tests which demonstrated high reliability, sensitivity and specificity to ACL and deep MCL injuries, offering a more objective and quantifiable method for assessing knee laxity compared to conventional clinical tests. This research supports the clinical

inclusion of these new laxity tests to create a more comprehensive knee examination. The ADSOEOB test, for instance, offers an alternative way to assess ATT by evaluating ligament tension under different conditions, complementing traditional anterior drawer and Lachman tests. The study's results suggest that integrating the ADSOEOB test could enhance the knee assessment process. Similarly, the Feagin Thomas test was found to be sensitive and specific for detecting deep MCL injuries, highlighting its potential value in clinical practice.

Impact of Muscle Guarding on Laxity Measurements: The cohort study investigated the effects of muscle guarding on knee laxity measurements using electromyography (EMG). It was discovered that muscle guarding is higher in the ACL injured population in comparison to the healthy cohort. In addition, it shows that muscle activation changes depending on the clinical test performed. There was no relationship found between laxity and muscle activation, however it is noted that more research is needed before concrete conclusions are made.

Comparison with Traditional Methods: The biomechanical models and protocols were compared with traditional arthrometry devices. Motion capture demonstrated marginal superior accuracy and consistency, along with the added benefit of providing comprehensive values of laxity across multiple planes. Although OMC may have limited direct clinical utility, it offers several advantages in researching ligament integrity. It provides detailed insights into measures of laxity by quantifying different clinical tests across multiple patients, which can inform and refine clinical practices. OMC is also versatile, allowing researchers to explore various research questions about the effects of laxity under different conditions, and to examine the biomechanical behaviour of ligaments in a controlled environment. Moreover, OMC can serve as a valuable tool for training wearable systems, ensuring these devices are accurate when measuring functional laxity in clinical settings. This capability enhances the development and validation of more advanced, data-driven diagnostic tools that can be used in routine clinical practice.

Overall, the biomechanical studies advanced the understanding of knee joint mechanics and provided robust tools for the quantification of knee laxity. These contributions are crucial for enhancing the diagnostic accuracy and reliability of ACL injury assessments.

10.2.3 Wearables and Machine Learning

The integration of wearable technologies and machine learning models in this research represents a promising step forward in the field of ACL injury diagnostics. While the study achieved a diagnostic accuracy of 71%, it is important to view this as an initial finding with the potential for improvement. Future advancements in model sophistication, model architecture, and expanded datasets may enable higher levels of accuracy. The key outcomes of this integration include:

Development of Wearable Sensor Systems: The research developed and tested wearable sensor systems, specifically inertial measurement units (IMUs), to capture real-time data on knee joint movements. These sensors provided effective proof of concept that off the shelf technology holds value within the continuous monitoring of knee biomechanics, offering valuable insights into clinical practice that with continued refinement and testing could be integrated into the clinical pathway.

Machine Learning Model for Diagnosis: A machine learning model, employing a neural network, was developed to analyse data from the wearable sensors. The data set of MRI-verified ACL injuries and healthy control subjects were trained and tested in this model. This model demonstrated the ability to accurately identify surrogate markers of anterior knee laxity, distinguishing between injured and healthy knees with precision of 71%. This level of accuracy establishes a baseline for wearables in ACL diagnostics and indicates potential for enhancement as model complexity and dataset size increase.

Validation and Performance: The machine learning model was validated against MRI verification and showed promising results. It achieved reasonable sensitivity (62%) and high specificity (75%), indicating its potential as a reliable diagnostic tool for ACL injuries. The model's performance highlights the feasibility of using wearable technology in clinical diagnostics, providing rapid and accurate assessments.

10.3 Implications of the Research

10.3.1 Clinical Translation

The findings from this research have significant clinical implementation that aim to enhance the current state of clinical practice.

Improved Diagnostic Accuracy: The integration of wearable technology within the diagnostic process has the potential to improve the objectivity element of clinical assessment. The development of advanced biomechanical models and the integration of wearable sensor technologies can provide an objective measure when assessing knee laxity. These tools offer detailed, quantifiable data on knee joint behaviour, which can significantly improve the ability to detect ACL injuries during clinical assessment, by reducing reliance on subjective clinical assessments, clinicians can make more precise diagnostic decisions and gain objective measures of patient functionality, leading to more informed, objective patient care. By eventually integrating these new tools into existing clinical workflows and developing user-friendly software for data interpretation, clinicians can make more precise diagnostic decisions, ultimately leading to more informed, objective patient care. To evaluate the effectiveness of these sensors, clinicians could compare the number of positive ACL injury diagnoses made using IMU sensors with the number of MRIs that confirm these diagnoses, versus the number of false negatives that occur when relying solely on traditional clinical assessments. This comparison would demonstrate how the use of IMU sensors can improve diagnostic accuracy.

Reduced Diagnosis Timeframes: The use of real-time data from wearable sensors and the efficiency of machine learning models has the potential to streamline the diagnostic process. By providing immediate, objective measurements of knee laxity, these technologies can reduce reliance on time-consuming traditional assessments and imaging techniques. Although further validation is needed, the initial findings suggest that incorporating these tools into clinical practice could lead to quicker identification of ACL injuries. This, in turn, would enable earlier intervention, which is critical for preventing further injury, reducing pressures on healthcare services, and optimising recovery outcomes.

Enhanced Patient Outcomes: Accurate and timely diagnosis is crucial for effective treatment. The advanced diagnostic tools developed in this research could lead to more personalised treatment plans, tailored to the specific biomechanical characteristics of each patient's injury. With more quantifiable data on knee laxity and functionality, clinicians can better understand the unique aspects of each injury, allowing for targeted interventions that address specific needs. Although this study did not directly investigate treatment outcomes or management plans, the ability to obtain precise biomechanical data could, in theory facilitate personalised

intervention. This has the potential to improve rehabilitation outcomes, reduce the risk of secondary injuries, and potentially decrease the incidence of long-term complications such as post-traumatic osteoarthritis (PTOA). Future research should explore how integrating these objective measures into clinical practice could further personalise patient management and enhance overall treatment efficacy.

Optimised Clinical Pathways: By providing objective, quantifiable data, the new diagnostic tools can help standardise the assessment process for ACL injuries. This standardisation can reduce variability in clinical practice, ensuring that all patients receive a high level of care regardless of the clinician or setting. Specialist care will always be beneficial, but more objective means of capturing patient's functionality allows for more streamlined care. Consistent and accurate assessments can also facilitate better communication and decision-making among healthcare providers.

10.3.1.1 Other Clinical Uses:

In addition to diagnosis, quantifying knee laxity, or surrogate markers of knee laxity with wearable sensors has benefit at other various stages of the patient management pathway. Whilst feasibility work is warranted, the potentiality should be noted, this includes:

Differentiating Management Routes: Directing patients between the surgical and conservative management routes is complex. Due to the varied patient outcomes of both options, high re-rupture rates, long recovery periods and associated risks, the decision for patients to venture down a specific path requires careful consideration and offers no certainty as to pre-injury functionality. By providing objective measures of knee stability, sensor data could help guide patient choices and support better patient outcomes.

Training Device for Laxity Assessment: Inexperienced clinicians have much lower diagnostic accuracy based off of their clinical assessment. It takes time and a plethora of exposure to fine-tune the ability to detect structural defects without imaging confirmation. By implementing wearable sensors to provide an objective measure of knee laxity, it can be used as a training tool to enhance their diagnostic assessment skills and understanding of knee biomechanics to improve clinical handling.

Tracking Rehabilitation Progress: Rehabilitation progression is often steered by generic functional outcomes and time milestones. For example, many ACL rehabilitation protocols

suggest progressing to more advanced exercises or activities based on a set number of weeks post-surgery, rather than individual patient recovery. Typically, milestones such as returning to light jogging might be recommended at 12-16 weeks, with a return to sports activities at 9-12 months, depending on a standard recovery timeline rather than patient-specific factors. Additionally, subjective parameters of strength and knee stability are often used to gauge improvement. These might include manual muscle testing or assessments of joint laxity, which can vary significantly between clinicians and lack objective precision. Precise tracking of knee function through real-time feedback is crucial because it allows for personalised adjustments to rehabilitation plans, potentially reducing the risk of re-injury and ensuring optimal recovery. By tailoring rehabilitation to the patient's actual progress rather than arbitrary timelines, we can enhance outcomes, improve patient safety, and promote more efficient use of healthcare resources.

Return to Play Thresholds: Re-injury rates are high among ACL injuries, particularly when athletes return to sports too soon. There is a careful balance between conservatively protecting surgically reconstructed grafts and allowing patients back into sports activities. High re-rupture rates can be attributed to the structural vulnerability of grafts and the deconditioned state of surrounding tissues during recovery. Because of this, careful management and slow, progressive rehabilitation exercises are necessary to restore strength and function gradually. Traditionally, return-to-play decisions have been guided by generic functional assessments, such as range of motion, muscle strength, and the ability to perform certain movements without pain. However, these assessments often lack the precision needed to gauge true readiness for high-impact activities. For instance, a patient might meet basic strength benchmarks but still have underlying knee instability that is not apparent through standard functional tests. Integrating objective measures of knee laxity and stability into rehabilitation protocols could provide a more comprehensive assessment of recovery. By using precise, data-driven thresholds, clinicians can better determine when an athlete has fully regained knee function and stability, thus minimizing the risk of re-injury. Objective metrics from wearable sensors could provide an additional layer of data-driven safety by helping clinicians make more informed return-to-play decisions based on objective measures of knee stability and function.

10.3.2 Technological Implications

The advancements in machine learning models using wearable sensor technology in this research have broad implications for their application in clinical settings.

Potential for Broader Applications: While this research focused on ACL injuries, the wearable sensors and machine learning models developed have potential applications in other areas of musculoskeletal health. Although different joints and conditions may require tailored sensor placement and testing protocols, the principles of real-time, objective monitoring can be adapted to diagnose and manage various other musculoskeletal and orthopaedic injuries. The success of this approach with ACL injuries, particularly due to the knee's role as a major weight-bearing joint, suggests that similar methodologies could be explored for other musculoskeletal conditions where precise movement tracking is crucial. However, it is essential to recognise that these technologies are not a one-size-fits-all solution and must be validated for each specific application to ensure effectiveness and relevance.

Integration with Existing Clinical Tools: Whilst wearable sensors are useful in isolation, the potential to integrate sensor data in conjunction with other clinical tools, such as subjective history, detailed MRI and arthroscopy findings, and functional outcomes, could expand the models' capabilities. Combining this data could provide a comprehensive prognostic view of the patient's condition, further improve the diagnostic picture, and help navigate patient decision making. This integration would require the development of more sophisticated diagnostic algorithms and treatment protocols.

Future Research and Development: The promising results from this research pave the way for further development of wearable diagnostic tools. Future studies can focus on refining sensor accuracy, exploring additional clinical tests, and enhancing machine learning algorithms to cover a wider range of conditions. Continued innovation in this field can lead to the creation of robust, multifunctional diagnostic platforms that transform clinical practice and patient care.

In summary, the clinical and technological implications of this research highlight the transformative potential of advanced diagnostic tools in improving the accuracy, efficiency, and overall quality of ACL injury management and other musculoskeletal conditions.

10.4 Future Work

10.4.1 Optical Motion Capture and Kinematic Assessment

Future work into the biomechanical evaluation of knee laxity amongst this patient group would allow for more robust conclusions to be made and increase the generalisability of the findings. Specific directions for these studies include:

Dynamic Imaging Techniques: There is no absolute way to quantify knee laxity. Optical motion capture is subject to soft tissue artefact movement, arthrometry is subject to large handling errors, cadaveric in-vitro measurement is not reflective of the conscious patient and dynamic MRI has poor image quality and associated accuracy. Comparing OMC values with dynamic MRI could potentially offer a way to cross-validate the accuracy of these methods as well as allowing the wearable sensor data to learn off of the dynamic MRI measures of laxity. However, such comparisons were beyond the scope of this study due to the significant costs and technical challenges associated with dynamic MRI, including the need for advanced imaging technology and expertise to manage and interpret the data effectively. Future research could explore these comparisons to enhance our understanding of knee laxity measurements, balancing the strengths and weaknesses of each technique to improve clinical assessment and management of knee injuries.

Inter-Rater Reliability: This research design included only one examiner. Whilst multiple subjects of both ACL injured and healthy control subjects were tested, re-test reliability was not assessed, and neither was inter-rater reliability. By repeating this protocol with multiple examiners, findings would be more generalizable to the clinical environment where patients are seen by multiple different clinicians. This approach will help to better reflect the variability encountered in clinical settings and ensure the robustness of the assessment protocols.

Diverse Patient Groups: Using larger sample sizes with more variation and combination of concomitant injury would enable a more comprehensive analysis of how different types of knee damage affect laxity and the overall diagnostic process.

Biomechanical insights into other structures: The focus of this research was on ACL tears, and within the OMC data capture, we successfully analysed laxity in two planes of motion, suggesting diagnostic indicators for the ACL and deep MCL. While the scope of the IMU data

extended only to ACL tears, there are ligaments across all peripheral joints that prevent movement in specific planes. Further research should evaluate the capability of OMC and wearable sensors to assess ligamentous integrity in these areas. This could potentially extend the application of this technology to inform clinical assessment for a variety of musculoskeletal conditions and joint mechanics. However, it is important to recognise that adapting these technologies to different joints and conditions will require thorough validation and may present unique challenges.

10.4.2 Wearables and Machine Learning Model

The application of wearables into clinical diagnosis holds the potential to improve patient care. In order to assure this, more comprehensive research including feasibility studies are necessary. Future work into wearables in this clinical application should focus on:

Increased Data Samples: By increasing the data points, including more participants that get fed into the neural networks, the model becomes more generalizable and reduces the risk of over fitting. This improved accuracy and performance has wider applicability and representation of the population and increases the model complexity.

Increasing data inputs into ML models: Adding more diverse datasets from various clinical tests and functional movements can significantly enhance the performance and sophistication of machine learning models. By including data from additional clinical tests, gait analysis, IMU data aligned with OMC data, and patients' subjective histories, the model benefits from improved accuracy and generalisation. This broader data spectrum increases model sophistication by making it more robust and reliable by allowing the model to learn from an increased data set, increasing its ability to handle variability in patient populations, and minimising bias. To achieve these advantages, future studies should aim to quantify the optimal volume and diversity of data required for the model.

Clinician Variability: Including data from clinical assessments performed by multiple clinician's further increases the generalisability of the model. Changes within rater's would be encapsulated and handled within the model which will improve the model's robustness and performance characteristics when applying the challenges of the real-world environment.

Integrating OMC Data for Enhanced Training: Incorporating the OMC data into the model can increase its complexity and training efficacy. The IMU data is already time stamped by

using the OMC data, by aligning the IMU captured data against the biomechanical gold standard, it would enrich the model's ability for wearable systems to detect nuanced changes in knee laxity, leading to more reliable diagnostics.

Feasibility Studies into Clinical Pathway of Diagnosis: feasibility studies on untrained, unseen data should be completed for assessing and enhancing the practicality and reliability of this machine learning model. It ensures that the model not only performs well in controlled test environments but also delivers robust, reliable results in diverse, real-world situations, thereby maximizing its effectiveness and utility.

Prototype building of functional wearable system: The next step in advancing IMU sensors as a diagnostic tool for ACL injuries involves developing a functional prototype of a wearable system, such as a knee sleeve. Collaborating with material science and mechanical engineering teams will be crucial to designing a prototype that integrates IMU sensors effectively while ensuring comfort, durability, and accuracy. Future work should focus on designing and constructing a knee sleeve that accommodates the technical requirements of the sensors and meets the practical needs of clinicians and patients. Input from clinicians will be essential to ensure the sleeve provides accurate diagnostic data and integrates seamlessly into clinical workflows. In contrast, feedback from patients will help ensure the device is comfortable, easy to wear, and user-friendly. This collaborative, interdisciplinary approach will help create a wearable system that is not only technologically advanced but also practical and feasible for everyday clinical use,

10.4.3 Technological Integration

Integrating wearable sensor data with other diagnostic tools represents a promising advancement in patient care, offering a more comprehensive and data-driven approach to healthcare. However, many technological innovations often fail at the implementation stage. To achieve the seamless integration of these technologies into clinical pathways, as discussed in Section 10.3.1, several critical factors must be addressed. These include ensuring compatibility with existing clinical workflows, providing adequate training for healthcare professionals, addressing data privacy concerns, and demonstrating the clinical and economic value of the technology. By focusing on these areas, we can better facilitate the adoption of wearable sensors in clinical practice and maximise their potential benefits for patient care.

Clinician buy in: Clinician buy-in is crucial for successfully integrating wearable technology into clinical practice. Healthcare providers need to understand and trust the technology to ensure adherence and effective use. Recognising the benefits to the clinical pathway helps clinicians view the technology as an asset rather than a burden. Moreover, they must effectively communicate these benefits to patients to enhance satisfaction and engagement. Involving clinicians early through training and workshops allows for iterative improvements to the device and fosters a sense of inclusion in the development process. Demonstrating the technology's positive impact on patient outcomes, workflow efficiency, and diagnostic precision through evidence-based results, case studies, and pilot projects can further build trust. Providing ongoing technical support, resources, and opportunities for feedback ensures clinicians feel supported throughout the integration process.

Ease of use: The device must be straightforward and user-friendly to ensure adoption in clinical settings, where healthcare professionals often face high workloads and time constraints. For successful integration, the device should operate reliably with minimal technical issues, as frequent malfunctions can lead to frustration and hinder its use. Conducting pilot studies and focus groups with clinicians and patients is essential to gather feedback on the interface and functionality, allowing for iterative refinements. These refinements can enhance the device's usability and ensure it aligns with clinical workflows, fostering greater adherence and optimising patient care by minimising time spent on troubleshooting.

Comprehensive Diagnostic Platforms: Once the prototype of the sleeve has been developed, the next steps would involve ensuring the data from the wearable system is in a useful and usable state for the clinicians. Developing the interface could include more than just the sensor data itself. As a potential next step, integrating the sensor data from the wearable system into a broader diagnostic platform could provide a more comprehensive and holistic view of the patient's condition. Such a platform might combine data from various sources, including real-time sensor outputs, X-ray results, clinical assessment notes, and the patient's medical history. Developing this kind of integrated system could make it easier for clinicians to access and interpret all relevant information in one place, potentially improving diagnostic accuracy and streamlining clinical workflows. By offering a fuller picture of the patient's condition, this approach could facilitate more informed decision-making and enhance patient

care. Further research and funding would be necessary to explore the feasibility of this integration and its potential impact on clinical pathways.

Electronic Health Record Integration: To ensure technological integration and clinical adoption, data from wearable sensors and biomechanical assessments must be seamlessly integrated into electronic health records. Feasibility studies, including focus groups with clinicians, can help identify the most effective ways to present this data and optimise interface configurations, facilitating better uptake in clinical settings. Integrating this data into EHR systems will not only save time during documentation but also enhance the robustness of patient records by including objective measures of knee laxity. This integration can improve communication among healthcare providers and enable more coordinated and efficient care.

Wider Data Analytics and AI: Identifying laxity or surrogate markers of laxity is just one component of what AI and ML models can do for the initial diagnosis element of this clinical setting. By leveraging data analytics from the sensors, the electronic health records, the diagnostic imaging outputs and other data, prediction and prognostic models could be developed to help guide patient decision making. Whilst this would require a more sophisticated ML model, the foundations for this can be built upon the outputs of this research. It could help direct personalised treatment plans and tailor advice to optimise patient outcomes. This approach would enhance the precision of care, enabling more effective and targeted interventions based on comprehensive data analysis.

10.5 Summary

In conclusion, this collective research advances the understanding of biomechanical differences in ACL-deficient patients. Joint laxity is a phenomenon that underpins clinical decision-making and functionality of patients, but it is currently accompanied by a lack of objective quantitative output, which leads to errors in clinical decision-making.

The initial scoping of current clinical practices, including the systematic review of diagnostic pathways and the survey of clinicians, highlighted significant inconsistencies and delays in ACL injury diagnosis. These insights emphasise the need for more standardised and efficient diagnostic protocols.

By exploring the nuanced biomechanical differences across multiple planes during clinical testing, this research has allowed for recommendations for changes within clinical handling

and has exposed the limitations and benefits of certain laxity tests. Investigating the effects of muscle guarding and gait deviations has also contributed to steering assessment recommendations. All of these biomechanical investigations have been instrumental in developing wearable devices that leverage machine learning to provide accurate, real-time assessments.

The wearable technology conceived from this study's biomechanical patterns has the potential to revolutionise the diagnosis and monitoring of ACL injuries. By providing quantitative measures of joint laxity, these devices can enhance the efficiency and accuracy of ACL tear identification, leading to more personalised and responsive treatment strategies. This research not only promises to improve clinical diagnostic processes but also paves the way for the integration of advanced technologies in patient management.

Overall, this thesis bridges the gap between biomechanical research and clinical application, offering new perspectives and tools for better patient outcomes in ACL injury management. The findings and innovations presented in this work have the potential to transform clinical practices, optimise patient care, and advance the field of musculoskeletal diagnostics.

Appendix A: Full Published Systematic Review

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Evaluating the diagnostic pathway for acute ACL injuries in trauma centres: a systematic review

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Abstract

Objective: This review sought to evaluate the literature on the initial assessment and diagnostic pathway for patients with a suspected Anterior Cruciate Ligament (ACL) tear.

Methods: MEDLINE, EMBASE, and CINAHL were systematically searched for eligible studies, PRISMA guidelines were followed. Studies were included if they used at least one assessment method to assess for ACL injury and participants were assessed at an acute trauma centre within 6-weeks of injury. Article quality was evaluated using the QUADAS-2 checklist.

Results: A total of 353 studies were assessed for eligibility, 347 were excluded for the following reasons: injuries were not assessed in an acute trauma setting, injuries were not acute, participants had previous ACL injuries or chronic joint deformities affecting the knee, participants were under 18, or participants included animals or cadavers. A total of six studies were included in the review. Common assessment methods included: laxity tests, joint effusion, inability to continue activity, and a history of a 'pop' and 'giving way' at the time of injury. Diagnostic accuracy varied greatly between the assessment method and the assessing clinician. Gold standard diagnostics were MRI and arthroscopy. A weighted meta-mean calculated the time to reach diagnosis to be 68.60 days [CI 23.94, 113.24]. The mean number of appointments to reach diagnosis varied from 2–5. Delay to surgery or surgical consultation ranged from 61 to 328 days.

Conclusion: Clinicians in the Emergency Department are not proficient in performing the assessment methods that are used for diagnosis in acute ACL injury. Reliance on specialist assessments or radiological methods inevitably increases the time to reach a diagnosis, which has repercussions on management options. There is an ever-growing demand to improve diagnostic accuracy and efficiency; further exploration into quantitative measures of instability would aid the assessment of peripheral joint assessment.

Keywords: ACL, Diagnosis, Acute injury, Emergency department, Care pathway

Introduction

Musculoskeletal complaints make up 30% of primary care consultations in the UK [1], with acute knee injuries accounting for approximately 5–8% of all acute injuries

seen in the Accident and Emergency unit (A&E) [2, 3]. Since the anterior cruciate ligament (ACL) is the main contributor to preventing tibia-femoral anterior translation and provides stability during rotation, the clinical assessment of acute ACL injury consists of laxity tests which assess for anterior and rotary stability of the knee, such as: Lachman's, anterior draw, and the pivot shift test. Clinical history and mechanism of injury can also act as a primary diagnostic indicator [4, 5]. ACL injuries

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are debilitating, for this reason, early diagnosis is key to facilitating efficient treatment outcomes.

Acute ACL injury is renowned to be difficult to assess and it is frequently missed by clinicians on initial assessment [6, 7]. Most acute ACL injuries present in trauma settings, such as A&E departments and minor injury units [3, 8, 9]. During the acute injury phase, joint effusion and muscular compensation are barriers to assessment [3, 8] where excessive joint effusion is postulated to reduce diagnostic accuracy to 12.7% [3]. Clinical assessment methods, whilst low cost, are subject to significant errors; diagnostic accuracy can be as low as 56% [6]. A paper published in 1996 stated diagnosis takes on average 21 months [10], a more recent paper exploring the assessment of ACLs in the emergency department concluded there has been little improvement since then, with only 14.4% of ACL injuries diagnosed at initial presentation [6].

Emergency physicians have poor diagnostic accuracy, as low as 25.9%, compared to more experienced professionals such as sports medicine physicians when assessing acute ACL injury [8, 11]. However, Perera's study emphasised that even with specialist training, orthopaedic physicians missed diagnosis in 28% of patients [8]. This reinforces that clinicians cannot ensure diagnostic accuracy with the current clinical assessment methods, thus emphasising the importance of more accurate diagnostic tests readily available at acute trauma centres to improve patient outcomes [11].

Early diagnosis is paramount as it can reduce the likelihood of the knee giving way, which is associated with secondary injury, specifically to the meniscus which can result in osteochondral damage [12]. Unfortunately, up to 50% of ACL injuries lead to post-traumatic osteoarthritis (PTOA) [13, 14]. ACL injuries lead to an increase

in anterolateral rotary instability [15], such instability, unless corrected by surgical or conservative means, leads to degradation on bony and cartilaginous structures which contributes to the progression of arthritic changes within the joint [16]. The British Orthopaedic Association not only highlights the importance of accurate, fast diagnosis, but it also recommends that any ACL injury is referred to a surgeon as soon as possible to facilitate optimal patient outcomes, be that surgical or conservative management [16].

Understanding current assessment methods and diagnostic pathways for patients with acute ACL tears is paramount to developing more efficient diagnosis recommendations and assessment measures. This article aims to systematically review the literature for assessing patients with suspected ACL tears that come in through the emergency department.

Materials and Methods

The PRISMA checklist was followed throughout in order to ensure a robust review process was followed.

Search strategy

The databases MEDLINE, EMBASE, and CINAHL were used to conduct the search, published articles up until the 25th of May 2021 were eligible for inclusion in the review. The search terms were either classed as headings or keywords. The Boolean search strategy was used to appropriately combine terms and retrieve the most relevant articles (Table 1). 'ACL' AND 'trauma centre' were the two topic groups, all keywords and subject headings within the topic heading 'ACL' were combined with 'OR'; this was repeated with the keywords and subject heading within the topic groups 'trauma centre'. Topic groups were then combined with 'AND'. After the automated

Table 1 Boolean search strategy

Topic Group	Subject headings	Keywords
ACL	MEDLINE EMBASE	Anterior cruciate ligament/ Exp Anterior cruciate ligament rupture/ Exp Anterior cruciate ligament injury/
	MEDLINE OVID	Anterior cruciate ligament/
	EBSCO CINAHL	MH "anterior cruciate ligament"
Trauma center	MEDLINE EMBASE	Emergency ward/ Exp emergency health service/ Delayed diagnosis/
	MEDLINE OVID	EXP Emergency medical services/ Delayed diagnosis/
	EBSCO CINAHL	MH "emergency medical services+" MH "diagnosis, delayed"
		Emergency department* OR emergency health service* OR emergency adj2 accident OR first contact practitioner* OR casualty OR triage* OR delay adj2 diagnosis OR late* adj1 diagnos* OR orthop/edic clinic* OR knee clinic* OR Emergency ward*

search using the terms listed in Table 1, a hand search was undertaken which cross-referenced the terms in Table 1 against the bibliographies of the relevant articles.

Eligibility criteria

The review scoped the current assessment methods and diagnostic pathways for ACL injury in the emergency department (ED) for patients. For articles to be eligible for the systematic review, they had to meet the following inclusion criteria: the assessment had to be completed in an Emergency Department, injury was acute on initial assessment (within 6 weeks), at least one clinical assessment tool was stated, and participants were deemed to have sustained an ACL injury. Articles were excluded if: participants had experienced a previous ACL injury, participants had known chronic joint deformities (such as osteoarthritis), animals or cadavers were included within the sample, the paper was not available in English, and if participants were under the age of 18. Study designs that were case reviews, case studies or series were also excluded.

Selection process

All articles identified from the search from the databases were exported to a reference manager software called Endnote X20 (Clarivate Analytics, Philadelphia, PA, USA). Duplicates were removed, all references were then exported to another reference management software called Covidence (Veritas Health Innovation, Melbourne, Australia). Articles were first screened by text and abstract, those who were deemed relevant underwent a full-text review. The articles were screened against the inclusion-exclusion criteria by two independent reviewers (N.A. and A.M), discrepancies between reviewers were then resolved by a discussion.

Studies that included participants under the age of 18 were contacted asking for data specific to the population of interest. A few articles did not specify whether the injury was acute or chronic, thus the authors of these articles were contacted for further information.

Data extraction

The following data were extracted from the selected articles: Aim; sample size; study design, time since injury, participant number, clinical assessment tool, reference standard, assessing clinician (profession and experience), time to reach diagnosis, the median number of appointments to reach diagnosis, the meantime to await surgery and diagnostic accuracy.

Statistical analysis

A meta mean with associated confidence intervals was calculated for the outcome: time to reach diagnosis.

Quality appraisal

The QUADAS-2 checklist (Appendix 1) was the quality appraisal assessment tool was used to assess papers. The QUADAS-2 is widely used for studies evaluating diagnostic accuracy assessment measures. It is made up of 4 domains: patient selection, index tests, reference standards, and flow and timing. As shown in Table 2, the first 3 domains are split into assessing sections A and B, A) risk of bias, and B) concerns regarding applicability. The 4th domain: flow and timing, did not include section B. The sections were comprised of signalling questions (Table 2) that would ultimately determine the 'risk of bias' and 'concern regarding applicability'. The QUADAS-2 is not designed to give an overall quality score, instead, it provides an overall judgment on the two assessment criteria. If a paper had more than one signalling question that was 'at high risk' (X) it was regarded as 'at risk of bias', the 'concern regarding applicability' was then assessed.

Results

A total of 673 articles were initially obtained across all three databases. After duplicates were removed, 353 articles were included in the review. Once the titles and abstracts were screened, 64 articles were eligible for a full-text review. Following this, six articles were identified as being appropriate for inclusion, Fig. 1 details the PRISMA diagram and the reasons for article exclusion at each stage.

Main characteristics of included studies

Table 3 details the main characteristics of the included studies of the review. The study completed by Clifford et al. [9] included participants with injuries that were outside of the acute timeframe (6 weeks), authors provided raw data for all participants and only the data of those who matched the inclusion criteria (61/82) were included in this review.

Article quality

The QUADAS-2 showed variation between studies, as represented in Table 4. The risk of bias in domain 1 was high for 50% of the articles [6, 7, 12], these were negatively impacted due to an insufficient sample size attributable to the absence of power calculations, inappropriate exclusion criteria, and a retrospective design including only patients who underwent arthroscopy.

Other factors that seemed to affect studies quality assessment were: insufficient description of their assessment methods [6, 12], injury verification using means that are not considered 'gold standard' for diagnosis [3], undefined timeframes between initial assessment and reference standard [6, 7, 12], and finally the inconsistent

Table 2 Signalling questions for QUADAS-2 quality assessment

Signaling questions for QUADAS-2 quality assessment	
Domain 1: patient selection	
A: risk or bias	Was a consecutive or random sample of patients enrolled? Did the study have appropriate exclusions? Was the study retrospective? Was a sufficient sample size used? Could the selection or patient have introduced bias? Are there concerns that the included patients do not match the review question?
B: concerns regarding applicability	
Domain 2: index test(s)	
A: risk or bias	Were the index test results interpreted without knowledge of the results of the reference standard? Were all the index tests specified and clearly explained? Could the conduct or interpretation of the index test have introduced bias? Is there concern that the index test, its conduct, or interpretation differ from the review question?
B: concerns regarding applicability	
Domain 3: reference standard	
A: risk or bias	Is the reference standard the 'gold standard' for ACL diagnosis? Were the reference standard results interpreted without knowledge of the results of the index test? Could the reference standard, its conduct, or its interpretation, have introduced bias? Is there concern that the target condition as defined by the reference standard does not match the review question?
B: concerns regarding applicability	
Domain 4: flow and timing	
A: risk of bias	Was there an appropriate interval between the index test and the reference standard? Was the time frame defined where the initial consultation (index test) and/or reference standard was completed? /Unclear Did all patients receive a reference standard? Did all patients receive the same reference standard? Were all patients included in the analysis? Could the patient flow have introduced bias?

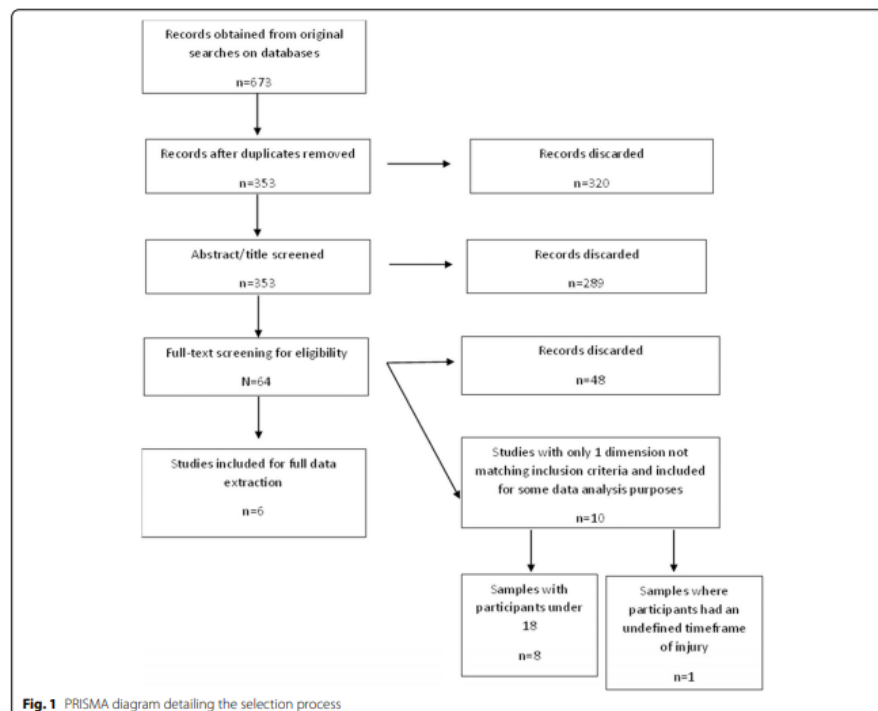
use of an injury verification method [9, 12]. Figure 2 represents the percentage of articles scoring high, low, and unclear for each domain.

Index tests

Table 5 presents the index tests and reference standards used in the studies included in the review. An index test, in this instance, is the initial assessment method(s) used to evaluate the knee. Passive laxity tests such as Lachman's, anterior drawer, and the pivot shift test were used to assess knee instability in two of the articles [7, 9]. Lee and Yun [17] used ultrasound and an unspecified clinical assessment as their index test. Joint effusion was part of the initial assessment in 3 of the studies [3, 7, 9], inability to continue activity was also an injury indicator in two of these articles [3, 9]. Another study's index tests comprised of palpation, temperature, and joint line tenderness [2], whilst a different article used X-Rays as a means of ruling out fractures [7]. Giving way and a 'pop' at the time of injury were a strong indicator of injury in two of the articles [9]. The other two studies left their initial assessment method unspecified [7, 9].

Reference standard

A reference standard, in the context of ACL injury, is a verification tool used to measure the accuracy of the respective index test. MRIs were used as a reference standard in many of the studies [3, 9, 17, 18]. Whereas, other participants were retrospectively recruited from ACL reconstructive surgeries, leaving arthroscopy as the designated reference standard [3, 7, 9]. In Clifford et al's study [9], only four participants did not have an MRI, of the 61 patients that met the inclusion criteria, 25 were initially diagnosed using MRI alone, another 25 were diagnosed from clinical examination findings, 9 participants diagnoses were confirmed from a combination of MRI and clinical assessments, and 2 had an arthroscopy. Hardy et al. [3] verified their index test with either an unspecified clinical assessment, MRI, or arthroscopy. They did not specify which participants had the respective reference standard [3]. Some studies did not specify their diagnosis verification, they simply eluded that ACL injury was confirmed [6, 12].



Time to reach diagnosis

Figure 3: meantime to reach diagnoses for individual sub-sample groups.

Table 6 represents the time taken to reach diagnosis, this varied between studies. Whilst Ball et al. [12] found that the implementation of an acute knee clinic reduced the time to reach diagnosis from 123 to 14 days. Lee and Yun's participants [17] were immediately scheduled for an MRI after their ultrasound on initial presentation to A&E, they reported diagnosis took an average of 3.8 days. Hardy et al. [3] observed a considerable increase in the delay to diagnosis when follow-ups were not scheduled, ranging from 29 to 198 days, when the patients who were diagnosed at initial consultation were removed this increased further to 229 days. Wang et al's [7] participants were all referred to an out-patient department to be seen by professionals in a specialist knee clinic within 7–14 days of initial presentation to the ED. It was eluded that confirmation of diagnosis was reached

at this outpatient visit, patients who had an aspiration performed on initial presentation took 6.7 days to be diagnosed; those who did not, took an average of 6 days. Parwaiz et al. [6] had 48.8% of the participants present to A&E, of these, only 5% were diagnosed on initial presentation, there was no further data on how long diagnosis took to be confirmed. Clifford et al's data revealed diagnosis took on average 115 days [9].

Statistical analysis

A weighted mean time to reach diagnosis yielded a result of 68.60 days [CI 23.94, 113.24] (Fig. 3).

Mean number of appointments to reach diagnosis

Three of the papers reported the number of appointments to reach diagnosis, ranging from 2 to 5 (Table 6). However, the number of appointments varied depending on the study design, those that only used imaging modalities took less time to reach diagnosis (2 appointments)

Table 3 Main characteristics of included studies

Author (Date)	Article title	Journal	Aims	Participants	Protocol
Ball et al (2010) [12]	The Impact of an Acute Knee Clinic	Annals of the Royal College of Surgeons of England	Evaluate the impact of an acute knee clinic on diagnosis and treatment for acute knee injuries	100	Design: • Prospective study • Consecutive sampling Methods: • Audit or timeframes and assessment process
Clifford et al (2021) [9]	Acute knee clinics are effective in reducing delay to diagnosis following anterior cruciate ligament injury	Knee	Investigate the impact of an acute knee clinic compared to the standard A&E pathway	61 (that matched the inclusion criteria)	Design: • Prospective study • Consecutive sampling Methods: • Physical examination • Imaging • Arthroscopy
Hardy et al (2017) [3]	The use of history to identify anterior cruciate ligament injuries in the acute trauma setting: the 'LIMP' index	Emergency Medicine Journal 2017	To investigate what clinical history features indicate ACL injuries	194 (163 available)	Design: • Prospective study • Consecutive sampling Methods: • Survey • Questionnaire • Physical examination • Imaging
Lee and Yun (2019) [17]	Feasibility of point-of-care knee ultrasonography for diagnosing anterior cruciate and posterior cruciate ligament tears in the ED	American Journal of Emergency Medicine 2019	To evaluate the use of ultrasound compared to MRI to diagnose ACL injury	62	Design: • Prospective study • Consecutive sampling Methods: • Physical examination • Imaging
Parwal et al (2016) [6]	Anterior cruciate ligament injury: A persistently difficult diagnosis	Knee	To investigate if there has been an improvement in ACL diagnosis over the last 20 years	160	Design: • Retrospective design • Consecutive sampling Methods: • Retrospective data extraction
Wang et al (2016) [7]	Efficacy of knee joint aspiration in patients with acute ACL injury in the emergency department	Injury 2016	To evaluate the impact of joint aspiration on the sensitivity of joint laxity tests on patients with ACL injuries through the emergency department	60	Design: • Retrospective design • Consecutive sampling Methods: • Retrospective data extraction • Physical examination • Imaging

Table 4 Methodological quality summary

STUDY	RISK OF BIAS				APPLICABILITY OF CONCERNS		
	Domain 1: PATIENT SELECTION	Domain 2: INDEX TEST	Domain 3: REFERENCE STANDARD	Domain 4: FLOW AND TIMING	Domain 1: PATIENT SELECTION	Domain 2: INDEX TEST	Domain 3: REFERENCE STANDARD
Ball et al. 2010 [12]	X	X	?	?	✓	?	?
Hardy et al. 2017 [3]	✓	✓	X	X	✓	✓	✓
Lee and Yun 2019 [17]	✓	✓	✓	✓	✓	✓	✓
Wang et al. 2016 [7]	X	✓	✓	?	✓	✓	✓
Parwaiz et al. 2016 [6]	X	X	✓	?	✓	?	✓
Clifford et al. 2021 [9]	✓	✓	✓	X	✓	✓	✓

KEY:
 ✓ = LOW
 X = HIGH
 ? = UNCLEAR

[17] compared to those that did not (3.3 and 5 appointments) [12, 9].

Assessing clinician

Table 7 displays the assessing clinicians and time until surgery. Ball et al. [12] did not specify the assessing clinician before the acute knee clinic was established. Patients assessed in the acute knee clinic were seen by a 'knee specialist'. The study by Lee and Yun [17] included a board-certified emergency physician with over 5 years of experience, and an MSK radiologist familiar with ultrasonography and its affiliation with ACL injury. The radiologist trained the emergency department practitioner in sonography prior to the study [17]. Hardy et al. [3] described the assessor in the acute knee clinic as 'a person highly trained in a particular branch of medicine', 22 were included, some of which were surgeons. Wang et al's [7] initial clinical assessment was performed by a junior orthopaedic surgeon; they were then followed up by a senior orthopaedic surgeon with over 10 years of experience [7]. Parwaiz and Clifford et al's patients were assessed by a variety of clinicians on initial presentation [6, 9].

Time until surgery

Not all studies included surgery data (Table 7). Those that did ranged from 61–328 days [3, 12]. Factors that increased time were not having an established acute knee clinic [12], not having a follow up arranged after initial consultation [3], and removing the cohort who were diagnosed on initial consultation [3].

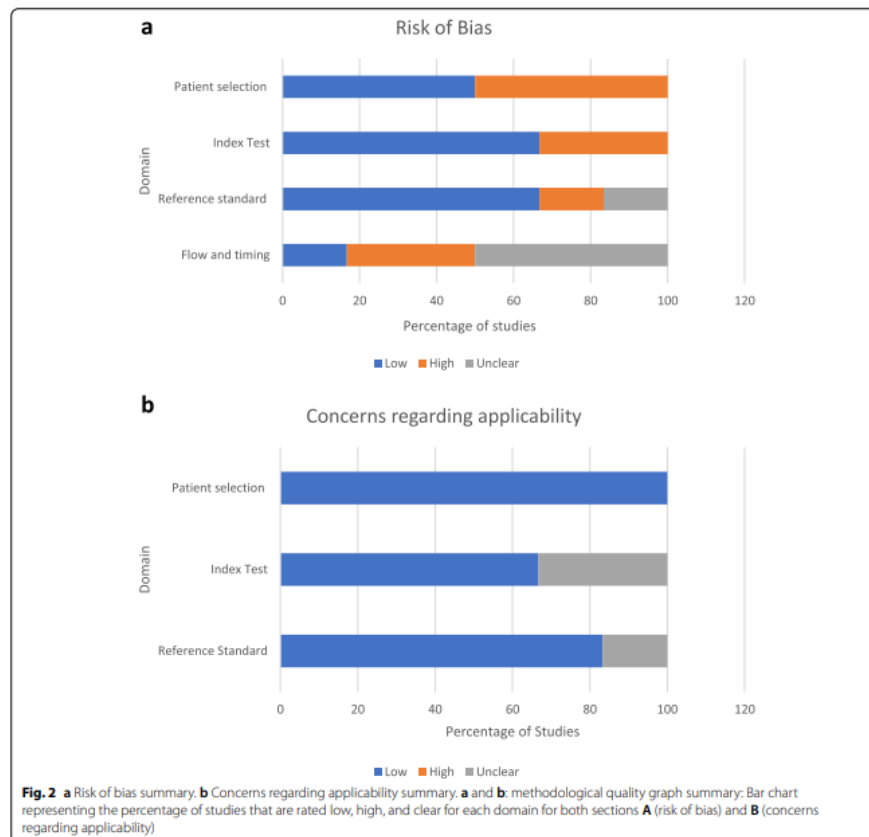
Diagnostic accuracy

Values of diagnostic accuracy were not available for all studies due to the way participants were recruited;

Table 8 demonstrates the values of diagnostic performance characteristics. Lee and Yun [17] recorded high accuracy of both ultrasound performers 1 and 2 of 91.9 and 93.6% respectively. Three of the studies only had values of true positive, and false negative cases; the participants that were assessed were of a population of confirmed ACL tears, meaning only sensitivity data was available [3, 7, 9]. In order for specificity, accuracy, PPV and NPV to be calculated, false positive and true negative data must be available [19, 20]. Hardy et al. [3] recorded that 99.5% of participants reported at least 1 facet of the LIMP index, 95.8% reported 2, 83.9% of participants reported 3, this dropped to 57.8% of participants reporting all 4 variables of the LIMP index. The Lachman's test yielded poor accuracy in Wang et al's study when initially performed in the Emergency Department at the time of injury in both the aspirated and non-aspirated cohort (47.1 and 40.5% respectively). This increased to 76.5% in the aspirated cohort when reviewed 2 weeks later in the outpatient department, this value was similar to the sensitivity reported by Clifford et al. (74.5%). Values for the pivot shift test varied massively (9.5–100%), the accuracy increased significantly in the aspirated knee group (from 11.8 to 76.5%). Clifford et al's study revealed an unremarkable sensitivity of 100%, however, this result was only based on 3 participants. Parwaiz et al. [6] did not have any data on the diagnostic accuracy of their assessment methods.

Discussion

This literature review evaluated the current diagnostic methods and assessment pathways available to patients presenting themselves to an Emergency Department with a suspected ACL injury. Although numerous papers



investigated diagnostic accuracy for ACL tears, only 6 met the inclusion criteria for this review.

A reoccurring theme in the literature, is that the time to reach a diagnosis is reliant on a thorough assessment at initial presentation, which is highly dependent on the proficiencies of the clinician in question. The difficulty arises when inexperienced assessors are presented with an acutely swollen knee [6, 7, 21], indicating a greater need for a quantifiable measure of instability amongst non-specialist departments, in order to reduce prolonged and false-negative diagnoses.

False positives and false negatives are the two obstacles within acute MSK injury assessment, if assessment criteria are too rigid and specific, false negatives occur; patients are discharged without the ACL injury identified [9, 22], which is a direct cause of lengthy diagnoses. Contrary to this, if assessment criteria are too comprehensive, although accuracy may be high, false-positive diagnoses will also be in abundance, thus encompassing many other differential diagnoses and overwhelming the service; a prime example of this is within Hardy et al's LIMP index [3].

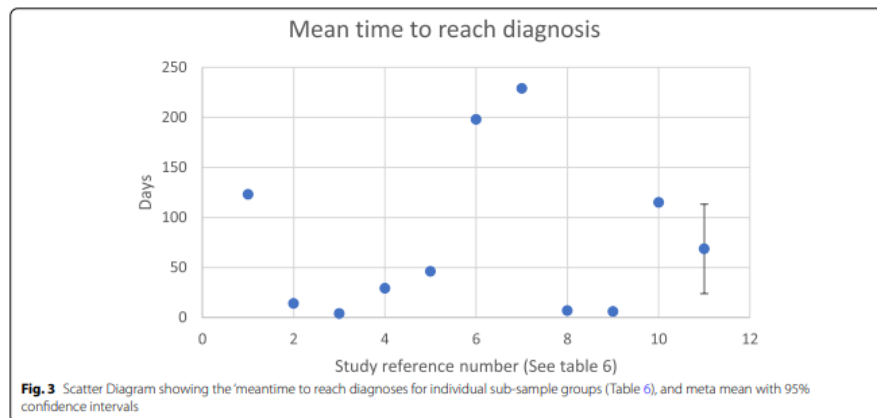
Table 5 Assessment methods

AIM	TEST	INDEX TEST	REFERENCE STANDARD
Laxity	Lachman's	(7, 9)	[9]
	INSTABILITY"	–	–
	Lever sign	–	–
	Pivot shift	(7, 9)	[9]
	Anterior drawer	(7, 9)	[9]
Range of movement	KT1000	–	–
	Active range of movement	(7)	–
	Passive range of movement	–	–
Swelling	Time delay swelling	(9)	–
	Joint effusion	(7, 9)	[9]
Functional ability	Weight bare	–	–
	Inability to continue activity	(9)	–
	Gait	–	–
Pain	Palpation	(7)	–
	Temperature	(7)	–
	Joint line tenderness	(7)	–
	Pain	–	–
Imaging	X-RAY	(9)	[9]
	Ultrasound	(17)	–
	CT	–	–
	MRI	–	[3, 9, 17]
Subjective assessment	Mechanism of Injury	–	–
	Lysholms functional score	–	–
	Locking	–	–
	Unspecified clinical history	(3, 6)	–
	Clicking	–	–
	Giving way	(9)	–
	Popping sound	(9)	–
	Limp index	(3, 9)	–
Unspecified assessment	Unspecified clinical assessment	(6, 17)	[3]
	Physicians' agreement	–	–
	Unspecified	(12)	[6, 12]
	Orthopaedic surgeon exam	–	–
Surgery	Anaesthetic eval	–	–
	Arthroscopy	–	[3, 7, 9]

Of the 6 papers reviewed, many articles had high risk of bias, this was primarily due to: (a) absence of power calculations, (b) retrospective design (c), unspecified index tests and reference standards, and (d) undefined timeframes between diagnostic tests and verification. Many studies were insufficiently powered or were retrospective in nature, sampling patients who had undergone reconstruction is not representative of the whole population. Both factors increase the risk of bias for domain 1. Unspecified index tests and reference standards lead to an inability to assess the risk of bias or concern regarding applicability, thus affecting the quality

scores of domains 2 and 3. Domain 4 was negatively impacted by undefined timeframes between the initial assessment (index test), and the diagnostic verification (reference standard). If this is not standardised amongst participants, longer wait times between the index test and reference standard will have repercussions on the recorded accuracy of the assessment method. Consequently, this quality review has identified many areas for improvement for studies evaluating diagnostic tests.

A plethora of index tests were used to identify ACL tears. Laxity tests were common and often accompanied by a subjective assessment and a history of the

**Table 6** Time to reach diagnosis

Author	Study components	Study reference number	Meantime to reach diagnosis (days)	Sample size	Mean number of appointments to reach diagnosis
Ball et al. 2010 [12]	Before acute knee clinic (AKC)	1	123	100	5
	Post-AKC	2	14	100	1
Lee and Yun 2019 [17]	Ultrasound	3	3.8	62	2
Hardy et al. 2017 [3]	Follow up arranged	4	29	120	–
	Follow up arranged with initial diagnosis removed	5	46	101	–
	No follow up arranged	6	198	43	–
	No follow up arranged with initial diagnosis removed	7	229	40	–
Wang et al. 2016 [7]	Aspirated knee group'	8	6.7	18	–
	Non-aspirated	9	6.0	42	–
Parwaiz et al. 2016 [6]	Those presenting to an Emergency Department	–	Not documented – although only 5% reached initially	78	–
Clifford et al. 2021 [9]	Whole Participant sample	10	115	61	3.3
Meta Mean		11	68.60	–	–

Table 6 showing the allocated study reference number for the sub-study components, including sample size, the meantime to reach diagnosis, and the mean number of appointments to reach diagnosis

mechanism of injury. Swelling alluded to a high suspicion of an ACL tear, however it was also a barrier to accurate assessment, as demonstrated by Wang et al. [7]. The authors theorised that aspiration reduces Substance P within the joint, which consequently decreases pain and prevents the patient from 'guarding' during joint instability tests [7].

When performed by a specialist clinician, the diagnostic performance characteristics of clinical tests increase

significantly [7] this is reflected by the inconsistencies amongst pivot shift test sensitivity (9.5–100%) [7, 9]. Diagnostic rates during initial assessment within the emergency department are reported as low as 5% [6], this is attributable to few clinicians performing stability tests during their assessment, often secondary to an unconfident skill set. Instead, patients of concern are triaged to specialist practitioners. Although this triaging pathway ensures a more accurate assessment, relying solely

Table 7 Tabulation of assessing clinician and delay to surgery

Author	Assessing clinician	Time until surgery
Ball et al. 2010 [12]	Unspecified	196
	'specialist'	126
Lee and Yun. 2019 [17]	Board-certified emergency physician with over 5 years of experience AND specialist MSK radiologist	–
Hardy et al. 2017 (time to initial appointment with surgeon) [3]	22 specialists	Follow up arranged 61 Follow up arranged with initial diagnosis removed 69 No follow up arranged 328 No follow up arranged with initial diagnosis removed 311
Wang et al. 2016 [7]	In the ED junior orthopaedic surgeon In the OPD follow-up senior orthopaedic surgeon	–
Parwaiz et al. 2016 [6]	advanced nurse practitioner OR A junior ED trainee OR A senior ED trainee	–
Clifford et al. 2021 [9]	triaged by an A&E Sister and assessed by an A&E physician 1 A&E registrar 1 triaged by nurses and assessed by an A&E Physician 4 normal adult triage route and then assessed by an A&E physician 53 adult triage and was then assessed by an emergency nurse practitioner 1 orthopaedic doctor 1	–

on specialists to undertake initial assessments relies on Emergency Department clinicians to be able to recognise those suspicious of ACL injury appropriately.

Radiological methods, such as ultrasound and X-rays [9, 17] were popular index tests. Ultrasound allows for fast comparison to the contralateral limb and is not subject to lengthy waitlists [17]. Although found useful in this review, ultrasound is not routinely used in the Emergency Department to assess for ACL injury due to the lack of available specialists in front door services [17].

X-rays were used as an assessment adjunct to rule out bony pathology. Nearly all studies used either MRI or arthroscopy to verify injury [11, 23–28] and these were the most popular assessment verification method [3, 7, 9, 17]. As such, both are considered as gold standard diagnostic approaches [29, 30], many clinicians within these studies would only confirm a diagnosis on their completion [9, 17], suggesting that many healthcare professionals are not confident in confirming diagnosis based on clinical assessment alone.

Although the findings of this paper reflect that the diagnostic accuracy of clinical assessment has high degrees of variability (Table 7), diagnostic accuracy of clinical assessments has been reported consistently high in other papers [31–35]. Though it must be considered that the majority of findings in such papers are based on injuries that are no longer in the acute time frame [31, 33,

34], which minimises the obstacles that are associated with acute assessment [7, 9]. In addition, the assessors were often highly experienced in assessing acute knee injury [33], and the respective diagnostic accuracy values were reported in a primary [32], or secondary care [31] setting, or they were performed under anaesthesia [35]; this is not reflective of front door assessing practitioners that complete the initial assessment screening process in the ED.

The varied time periods to reach a diagnosis is attributable to the differences in the study design and the assessing clinician. The weighted mean (68.60 days) for the time to reach diagnosis is not necessarily representative of clinical practice. Diagnostic performance characteristics were highest in the studies using ultrasound and joint aspiration [7, 17], both of which are unsurprising due to the expertise required to undertake these assessment methods.

There is a clear correlation between faster diagnoses and more efficient diagnostic pathways. Late diagnosis leads to delayed surgical review [3, 12], as illustrated in Table 7; this impacts the optimal management pathways. Those with clinical follow-ups arranged reached diagnosis in a shorter period [3, 7, 12]. Lengthy diagnoses were a consequence of prolonged referral times between initial assessment and a specialist review, resulting in multiple appointments before a diagnosis is reached [12] (Table 6).

Table 8 Diagnostic accuracy of index tests

Authors	Diagnostic accuracy			
Ball et al. 2010 [12]	Unspecified			
Lee and Yun 2019 [17]		Ultrasound performer 1 (%)	Ultrasound performer 2 (%)	
	Sensitivity	90.6	96.9	
	Specificity	93.3	90	
	Positive predictive value (PPV)	93.6	91.2	
	Negative Predictive value (NPV)	90.3	96.4	
	Accuracy	91.9	93.6	
Hardy et al. 2017 [3]	Sensitivity	All 4 facets	57.8%	
		3 facets	83.9%	
		2 facets	95.8%	
		1 facet	99.5%	
Wang et al. 2016 [7]		Group 1- Aspirated knee (Sensitivity)	Group 2- non-Aspirated knee (Sensitivity)	
		ED	Lachman's	47.1%
			Pivot shift	11.8%
		OPD	Lachman's	76.5%
			Pivot shift	76.5%
			Lachman's	40.5%
			Pivot shift	9.5%
			Lachman's	47.5%
			Pivot shift	31.0%
Parwaiz et al. 2016 [6]	Unspecified			
Clifford et al. 2021 [9]			Sensitivity	
		Lachman's	74.5% ^a	
		Anterior Drawer	61.4% ^a	
		Pivot Shift	100% ^a	

Table 8 Table showing the accuracy, sensitivity, specific NPV and PPV of assessment methods. The performance characteristics were dependent on the data available in the articles

^aValues were re-calculated from the raw data sent by the authors. Only the population of interest were included in these values. Participants outside of the 6-week timeframe, under 18, or assessed outside of A&E were excluded

This is secondary to ineffective initial assessments and subsequent false negatives on clinical testing.

The effects of lengthy diagnosis are exposed over time, ACL deficient knees are associated with an increase in "giving way" episodes and knee instability. Whilst it has not yet been confirmed that an earlier diagnosis leads to a decreased chance in developing PTOA, it is not naïve to assume that earlier intervention would directly improve patient outcomes. ACL tears give rise to rotational instability and varus thrust [16, 36], those with a varus thrust have a 3-fold increase in developing osteoarthritis, furthermore those with defined OA are often ACL deficient or severely dysfunctional [16, 36]. Receiving the appropriate management, whether surgical or conservative, aims to prevent "giving way" and to correct gait abnormalities, which in turn, prevent subsequent injury deterioration and development of PTOA.

Limitations must be considered when analysing the review. Some of the included papers had high risk of bias, thus affecting the evidence of conclusions. Most of

the data outcomes showed heterogeneity, subsequently a meta-analysis could not be completed. The time to reach diagnosis is hard to definitively timestamp, clinical impressions and working diagnoses are often made early on, the question therefore arises: when is diagnosis reached? Also, it must be considered that the 'time taken until surgery' was noted as an outcome for 2 of the studies, this is not representative of the conservative management group; complexities arise when trying to define a point in time to represent delayed diagnosis within this patient group. The knee is the most commonly injured joint within sport, with 90% of knee injuries involving the ACL [37]. This study only reflects a small proportion of these, more reviews like this must be undertaken for more data to be available and represented in this area. However, it must be recognised that the lack of publications in this area are a consequence of the adversities in setting up trials in acute settings and phases of injury. Finally, excluding participants under the age of 18 reduced our sample size, though this was

appropriate for this review as this was only considering those who are skeletally mature and within an adult healthcare pathway, further reviews into the paediatric population would be of use to evaluate repercussions of late diagnoses in the younger population.

Conclusion

Clinical tests are highly subjective in assessing acute knee injury. A&E clinicians are often not proficient in performing instability tests which can lead to inappropriate triaging of patients with an ACL injury. Radiological verification is unsurprisingly accurate; however, it is unattainable to seek immediate radiological verification for this patient group. ACL tears lead to inherent knee instability, if appropriate management is not sought efficiently, this can lead to an increased chance of developing PTOA. Further research should begin to investigate methods of instability quantification in order to tackle the repercussions of delayed diagnoses.

Abbreviations

ACL: Anterior cruciate ligament; A&E: Accident and emergency; ROM: Range of movement; TOI: Time of injury; PTOA: Post-traumatic osteoarthritis; MRI: Magnetic resonance imaging; MSK: Musculoskeletal.

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Authors' contributions

All authors have read and approved the manuscript. N. A and A. MG were involved in the manuscript preparation, article review and quality assessment. N. A completed the study design, N. A and M. B were involved in the statistical analysis database interpretation, and all authors part-took in manuscript revision. The author(s) read and approved the final manuscript.

Authors' information

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Availability of data and materials

All data generated or analysed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Appendix B: Survey for clinicians assessing patients with suspected ACL tears.

1. What is your professional title?

(Please circle/highlight as appropriate)

Advanced nurse practitioner

- A. Physiotherapist
- B. Junior doctor
- C. Speciality doctor
- D. Consultant
- E. Other (Please specify below)

2. What is your speciality? (If you are rotational or junior staff please state accordingly)

(Please circle/highlight as appropriate)

- A. Orthopaedics
- B. MSK
- C. A&E
- D. Junior rotational staff (please specify current rotation)
- E. GP
- F. Other (Please specify)

3. What is your primary place of work?

(Please circle/highlight as appropriate)

- A. NHS
- B. Elite sports

- C. Private MSK/orthopaedic clinic
- D. Armed forces
- E. Other (please specify)

4. Within your place of work, what setting do you work in?

(Please circle/highlight as appropriate)

- A. A&E
- B. Fracture clinic
- C. Acute knee clinic
- D. Soft Tissue injury clinic
- E. General MSK clinic
- F. Private MSK clinic
- G. Pitch side support work
- H. GP
- I. Other (Please specify)

5. How many years of experience do you have assessing acute knee injury?

(Please state below)

--

6. If a patient came in with an acute knee injury, what subjective questions would you ask them to rule out or consider an ACL injury?

Please rank below the following starting what you deem most important when assessing for an ACL injury.

- Mechanism of injury
- PMH
- Pain
- Pop/snap
- Giving way
- Joint effusion
- Locking
- ROM
- WB issues
- Changes in gait
- Ability to continue activity.

7. If a patient came in with an acute knee injury, how would you prioritise the following clinical assessment methods, in order to rule out or consider an ACL injury?

Please rank in order of importance

- Lachman's
- Anterior drawer
- Pivot shift
- AROM
- PROM
- GAIT analysis
- Strength testing
- Palpation
- Effusion assessment
- Functional movement testing (STS, squat, single leg work etc)

8. How confident are you that you could 'feel' for instability and make appropriate conclusions?

(Please circle answer)

- A. Very confident
- B. Somewhat confident
- C. Somewhat unconfident
- D. Very Unconfident

9. Who would you refer this patient on to if you were suspicious of an ACL injury?

(Choose all those that apply)

- A. For a surgical opinion
- B. For a Physiotherapy assessment
- C. To fracture clinic
- D. To an acute injury clinic
- E. To a soft tissue clinic
- F. Other (Please specify)

10. Would you feel confident diagnosing a patient with an ACL tear off YOUR assessment without imaging or surgical verification?

(Please state yes/no below)

Yes

No

11. If a patient presented with an acute knee injury, prioritise the following imaging modalities you would want to assist your assessment?

(Rank in order of those you feel appropriate)

- X ray
- MRI
- Ultrasound

12. Would you consider bracing? If so what brace, and for how long?

13. What advice would you give a patient that was highly suspicious of an ACL injury?

14. Please upload any patient advice leaflets/documents you would provide to where you are suspicious or have diagnosed and ACL injury.

****Upload file option****

Appendix C: Search Strategy for Scoping Review

Subject Groupings		Subject Headings		Key words
Knee Instability	MEDLINE EMBASE	anterior cruciate ligament injury/	MEDLINE EMBASE	tibial rotation* or (knee*1 adj3 instability)).mp OR (knee* adj3 laxity).mp. OR (Anterior Cruciate Ligament* adj3 (laxity or instability)).mp. OR ACL injury.mp. OR ((anterior cruciate ligament adj3 injury) or anterior cruciate ligament reconstruction).mp. OR (anterior cruciate ligament deficient or ACL deficient or anterior cruciate ligament insufficien* or ACL insuficien*).mp.
	MEDLINE OVID	Anterior Cruciate Ligament Injuries/	MEDLINE OVID	tibial rotation*.mp.OR (Knee*1 adj3 instability).mp.OR (knee* adj3 laxity).mp. OR (anterior cruciate ligament* adj3 OR (laxity or instability)).mp. OR ACL injury.mp. OR (anterior cruciate ligament adj3 injury).mp. OR (anterior cruciate ligament deficient or ACL deficient or anterior cruciate ligament insufficien* or ACL insuficien*).mp.
		Anterior Cruciate Ligament Reconstruction/		
	EBSCO CINAHL	(MH "Anterior Cruciate Ligament Injuries")	EBSCO CINAHL	"tibial rotation*" OR Knee* N2 instability OR knee* N2 laxity OR "anterior cruciate ligament injury" OR acl injuryOR anterior cruciate ligament* N2 (laxity or instability) OR anterior cruciate ligament N2 injury OR "anterior cruciate ligament deficient OR ACL deficient or anterior cruciate ligament insufficien* OR ACL insuficien*"
		(MH "Anterior Cruciate Ligament Reconstruction")		
	Scopus	N/A	Scopus	((TITLE-ABS-KEY ("anterior cruciate ligament deficient" OR "acl deficient" OR "anterior cruciate ligament insufficien*" OR "acl insuficien*")) OR (

				TITLE-ABS-KEY ("anterior cruciate ligament" W/3 reconstruction)) OR (TITLE-ABS-KEY (acl W/3 injury)) OR (TITLE-ABS-KEY ("anterior cruciate ligament" W/3 injury)) OR (TITLE-ABS-KEY (knee* W/3 instability)) OR (TITLE-ABS-KEY (tibial W/2 rotation*)) OR (TITLE-ABS-KEY ("anterior cruciate ligament" W/3 laxity OR instability)) OR (TITLE-ABS-KEY (acl)) OR (TITLE-ABS-KEY (knee* W/3 instability)))
Method of assessment	MEDLINE EMBASE	exp wearable sensor/	MEDLINE EMBASE	wearable*.mp. OR optical motion capture.mp. OR (Dynamic adj2 MRI*).mp OR inertial measurement unit.mp. OR or IMU*1.mp. or KiRA.mp. OR acceleration.mp. OR KT1000.mp. OR accelerometer.mp. OR (gyroscope sensor* OR gyroscope).mp. OR (non-invasive assessment* or Knee excursion*).mp. OR (inertial sensor* OR kinematic 3-D analysis).mp. OR (electromagnetic tracking system* OR Knee joint moment).mp.
		motion analysis system/		
		exp inertial sensor/		
		accelerometer/		
	MEDLINE OVID	exp Wearable Electronic Devices/ OR Acceleration/ OR Accelerometry/	MEDLINE OVID	wearable sensor.mp. OR (motion analysis system or optical motion capture).mp.OR (dynamic adj2 MRI).mp. OR inertial measurement unit.mp. OR inertial measurement unit.mp.OR (accelerometer or IMU*1 or KiRA or acceleration or KT1000).mp.OR (gyroscope sensor* or gyroscope).mp. OR (non-invasive assessment* or knee excursion*).mp.OR (inertial sensor* or kinematic 3-D analysis).mp.OR (electromagnetic tracking

				system* or knee joint moment).mp
	EBSCO CINAHL	(MH "Wearable Sensors+") (MM "Motion Analysis Systems") OR (MH "Accelerometers")	EBSCO CINAHL	"wearable sensor" OR "wearable*" OR "motion analysis" OR "optical motion capture*" OR "Dynamic N1 MRI*" OR "inertial measurement unit" OR "inertial N1 sensor*" OR "accelerometer" OR IMU* or KiRA or acceleration or KT1000 OR "gyroscope*" OR non-invasive assessment OR knee excursion* OR kinematic N2 Assessment OR electromagnetic tracking system* OR Knee joint moment
	SCOPUS	N/A	SCOPUS	((TITLE-ABS-KEY ("kinematic 3d analysis" OR {knee joint moment})) OR (TITLE-ABS-KEY ((inertial W/1 sensor*))) OR (TITLE-ABS-KEY (({knee excursion}))) OR (TITLE-ABS-KEY (("non invasive assessment*"))) OR (TITLE-ABS-KEY (accelerometer OR kira OR imu OR imus OR acceleratio* OR kt1000)) OR (TITLE-ABS-KEY ("inertial measurement unit" OR "inertial sensor*")) OR (TITLE-ABS-KEY ("optical motion capture")) OR (TITLE-ABS-KEY ((dynamic W/2 mri))) OR (TITLE-ABS-KEY ("motion analysis system*")) OR (TITLE-ABS-KEY ("wearable sensor*")) OR (TITLE-ABS-KEY (wearable*)))
Clinical test	MEDLINE EMBASE	gait/		(Pivot Shift* OR Pivot-shift).mp. anterior draw*.mp. OR gait analysis.mp. OR gait adaptation*.mp. OR lateral laxity.mp. OR step-up-and-over test.mp. OR Dynamic Knee Loading.mp. OR Lachman*.mp.

	MEDLINE OVID	exp Gait/ OR exp Gait Analysis/		(pivot shift* or pivot-shift*).mp OR anterior draw*.mp. OR gait analysis.mp. OR (gait adaptation* or lateral laxity or step-up-and-over test or dynamic knee loading).mp. OR Lachman*.mp.
	EBSCO CINAHL	(MH "Gait Analysis")		Pivot-shift OR anterior draw* OR "gait" OR gait adaptation OR lateral laxity OR step-up-and- over test OR dynamic knee loading OR "Lachman"
		(MH "Gait")		
	Scopus	N/A		((TITLE-ABS-KEY ("pivot shift")) OR (TITLE-ABS-KEY ("anterior draw*")) OR (TITLE-ABS-KEY ("anterior draw*") OR gait OR "gait adaptation" OR {lateral laxity} OR {step-up-and-over test} OR {dynamic knee loading}) OR (TITLE-ABS-KEY (Lachman*)))

Appendix D: Laxity tables

Table 57: Comparative Analysis of Anterior Tibial Translation (ATT) Range in Millimetres Across Two Group Cohorts Using Non-Parametric Tests for Three Clinical Tests.

	AD	LM	ADSOEOB
Mann-Whitney U	66556.000	151875.000	23958.000
Wilcoxon W	362621.000	611236.000	107394.000
Z	-10.572	-6.650	-7.755
Asymo. Sig. (2-Tailed)	<.001	<.001	<.001

Table 58: Effect Sizes for Each Clinical Test when assessing Anterior Tibial Translation (ATT) Range in Millimetres

	AD	LM	ADSOEOB
Effect Size	0.506	0.227	0.392

Table 59: Independent T-Test Comparison of Anterior Tibial Translation (ATT) Ratios Between ACL-Injured and Healthy Cohorts Using the Anterior drawer Test.

		F	Sig	T	Df	Significance		Mean difference	Std. Error Difference	Difference	
						OneSided p	TwoSided p	Mean diff	Std. error diff	Lower	Upper
Range MaxMaxNorm	Equal variances assumed	2.535	0.118	-3.742	47	<0.001	<0.001	-0.411	0.110	-0.632	-0.190
	Equal variances not assumed			-3.644	36.471	<0.001	<0.001	-0.411	0.113	-0.640	-0.182
RangeMeanMeanNorm	Equal variances assumed	5.802	0.020	-4.234	47	<0.001	<0.001	-0.543	-0.801	-0.801	-0.285
	Equal variances not assumed			-4.069	30.522	<0.001	<0.001	-0.543	-0.815	-0.815	-0.271

Table 60: Independent T-Test Comparison of Anterior Tibial Translation (ATT) Ratios Between ACL-Injured and Healthy Cohorts Using the Lachman Test.

		F	Sig	T	Df	Significance		Mean difference	Std. Error Difference	Difference	
						OneSided p	TwoSided p	Mean diff	Std. error diff	Lower	Upper
Range MaxMaxNorm	Equal variances assumed	.004	.952	-2.549	47	.007	.014	-.242	.095	-.433	-.051
	Equal variances not assumed			-2.554	46.621	.007	.014	-.242	.095	-.433	-.051
RangeMeanMeanNorm	Equal variances assumed	.432	.514	-2.629	47	.006	.012	-.244	.093	-.431	-.057
	Equal variances not assumed			-2.650	47.000	.005	.011	-.244	.092	-.429	-.059

Table 61: Independent T-Test Comparison of Anterior Tibial Translation (ATT) Ratios Between ACL-Injured and Healthy Cohorts Using the Anterior drawer Sat on the Edge of the Bed Test.

		F	Sig	T	Df	Significance		Mean difference	Std. Error Difference	Difference	
						OneSided p	TwoSided p	Mean diff	Std. error diff	Lower	Upper
Range MaxMaxNorm	Equal variances assumed	0.08	0.79	-2.32	39	0.01	0.03	-0.26	0.08	0.79	-2.32
	Equal variances not assumed	0	0	-2.32	38.25	0.01	0.03	-0.26	0	0	-2.32
RangeMeanMeanNorm	Equal variances assumed	0.04	0.85	-2.22	39	0.02	0.03	-0.25	0.04	0.85	-2.22
	Equal variances not assumed	0	0	-2.22	37.71	0.02	0.03	-0.25	0	0	-2.22

Table 62: Analysis of Variance (ANOVA) Examination of Anterior Tibial Translation (ATT) Range (mm) Among ACL-Injured Cohorts: No Additional Ligament Injuries, One Additional Ligament Involved, and Two Additional Ligaments Involved.

	Sum of Squares	df	Mean Square	F	Sig
Between Groups	125.829	2	62.915	3.521	0.030
Within Groups	16026.815	897	17.867		
Total	16152.644	899			

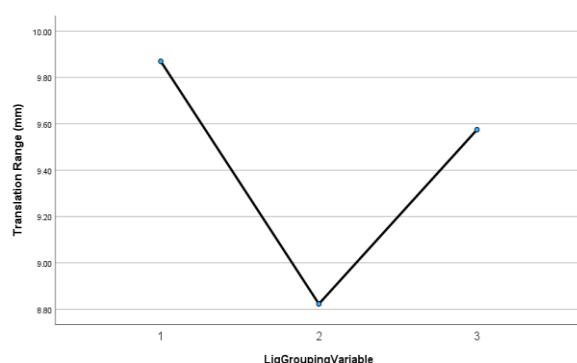


Figure 70: Means Plot for the ATT Range (mm) for ACL injured cohort with additional injuries.

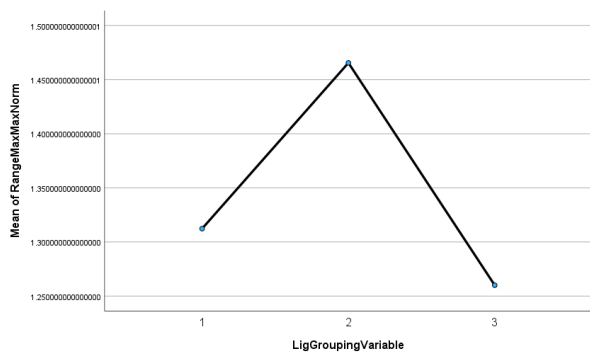


Figure 72: Means Plot Illustrating Variations in Average ATT Ratios for Participants with Additional Ligamentous Injuries, Focused on RangeMaxMaxNorm Measurements.

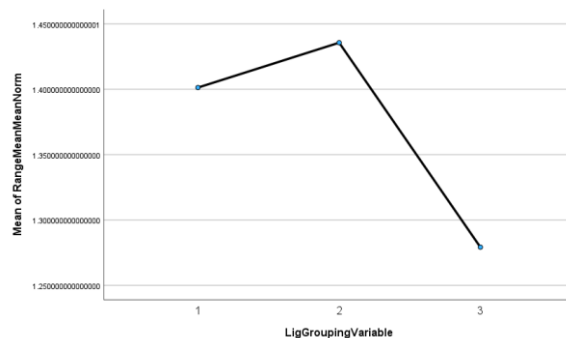


Figure 72: Means Plot Illustrating Variations in Average ATT Ratios for Participants with Additional Ligamentous Injuries, Focused on RangeMeanMeanNorm Measurements.

Table 63: Analysis of Variance (ANOVA) Examination of Anterior Tibial Translation (ATT) Ratios Among ACL-Injured Cohorts: No Additional Ligament Injuries, One Additional Ligament Involved, and Two Additional Ligaments Involved.

ANOVA		Sum of Squares	df	Mean Square	F	Sig.
RangeMaxMaxNorm	Between Groups	.353	2	.176	1.187	.312
	Within Groups	9.662	65	.149		
	Total	10.015	67			
RangeMeanMeanNorm	Between Groups	.295	2	.147	.744	.479
	Within Groups	12.864	65	.198		
	Total	13.159	67			

Table 64: Analysis of Variance (ANOVA) Examination of Anterior Tibial Translation (ATT) Range (mm) Among ACL-Injured Cohorts: No Additional Meniscus Injuries, One Meniscus Involved, and Two Meniscus Involved.

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	672.230	2	336.115	19.895	<.001
Within Groups	15576.725	922	16.894		
Total	16248.955	924			

Group 1: ACL Without Meniscus; Group 2: ACL +1 Meniscus; Group 3: ACL+2 Meniscus

Table 65: Analysis of Variance (ANOVA) Examination of Anterior Tibial Translation (ATT) Ratios Among ACL-Injured Cohorts: No Additional Meniscus Injuries, One Meniscus Involved, and Two Meniscus Involved.

ANOVA		Sum of Squares	df	Mean Square	F	Sig.
RangeMaxMaxNorm	Between Groups	.693	2	.347	2.416	.097
	Within Groups	9.322	65	.143		
	Total	10.015	67			
RangeMeanMeanNorm	Between Groups	.796	2	.398	2.094	.131
	Within Groups	12.362	65	.190		
	Total	13.159	67			

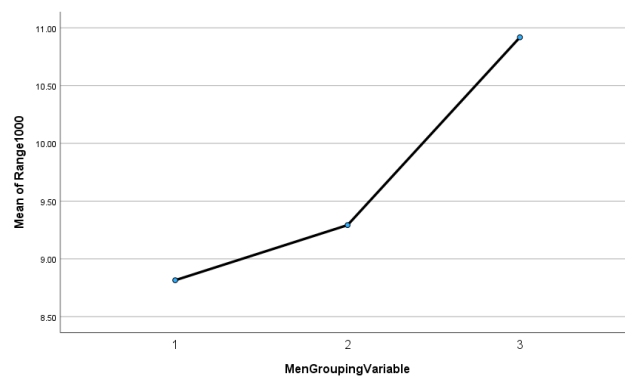


Figure 73: Means Plot Illustrating Variations in Average ATT Range (mm) for Participants with Additional Meniscus Injuries

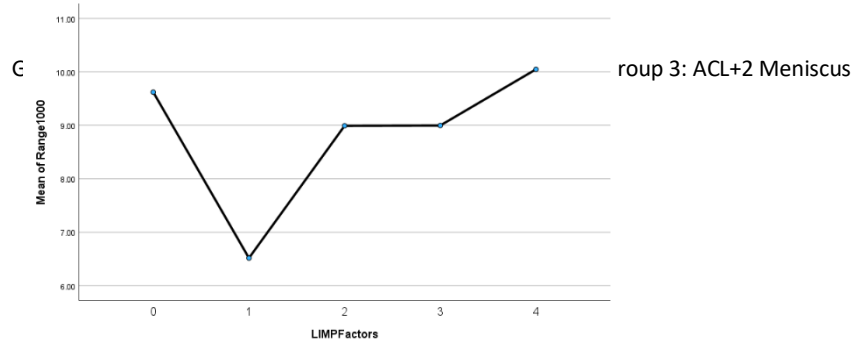


Figure 74: Means Plot of Anterior Tibial Translation (ATT) Range by LIMP Factor Levels. This visualization displays the average ATT range in millimetres, along with variability, for participants grouped according to the number of factors in their LIMP index.

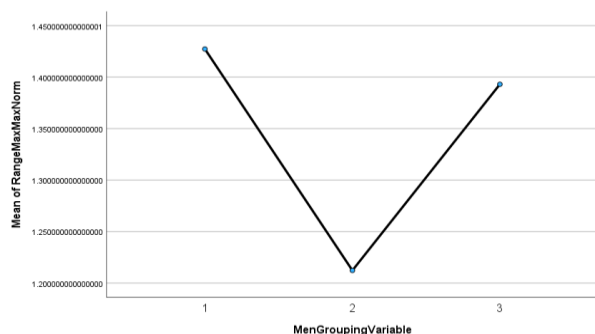


Figure 75: Means Plot Illustrating Variations in Average ATT Ratios for Participants with Additional Meniscus Injuries, Focused on RangeMaxMaxNorm Measurements.

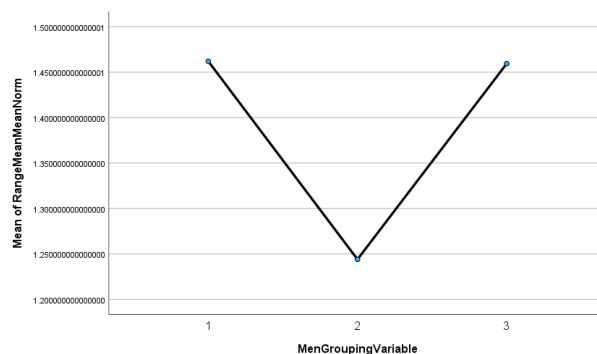


Figure 76: Means Plot Illustrating Variations in Average ATT Ratios for Participants with Additional Meniscus Injuries, Focused on RangeMeanMeanNorm Measurements.

Group 1: ACL Without Meniscus; Group 2: ACL +1 Meniscus; Group 3: ACL+2 Meniscus

Table 66: ANOVA Results showing variance in Anterior Tibial Translation (ATT) Range in Millimetres Among LIMP Index Groups.

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	607.874	4	151.968	8.750	<.001
Within Groups	15544.771	895	17.368		
Total	16152.644	899			

Table 67: ANOVA Analysis of Variance in ATT Ratios Among Different LIMP Index Groupings.

ANOVA						
Ratio Type		Sum of Squares	df	Mean Square	F	Sig.
RangeMaxMaxNorm	Between Groups	.605	4	.151	1.013	.407
	Within Groups	9.409	63	.149		
	Total	10.015	67			
RangeMeanMeanNorm	Between Groups	.607	4	.152	.762	.554
	Within Groups	12.551	63	.199		
	Total	13.159	67			

Table 68: Normality Distribution Calculations for the Lachmeter Readings of Injured cohort

Tests of Normality						
	Kolmogorov-Smirnov			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
LachUniqueValue	.169	19	.159	.963	19	.640

Table 69: Normality Distribution Calculations for the Lachmeter Readings of Healthy Cohort

Tests of Normality						
	Kolmogorov-Smirnov ^a			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
LachUniqueValue	.115	42	.185	.929	42	.012

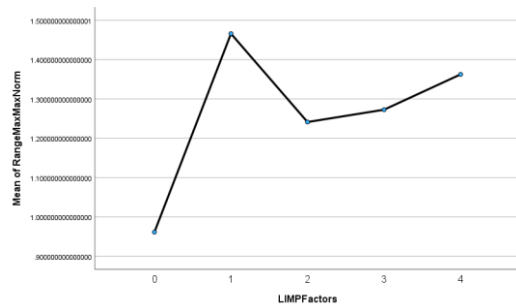


Figure 78: Means Plot of Anterior Tibial Translation (ATT) Range by LIMP Factor Levels. This visualization displays the average ATT Ratio RangeMaxMaxNorm for participants grouped according to the number of factors in their LIMP index.

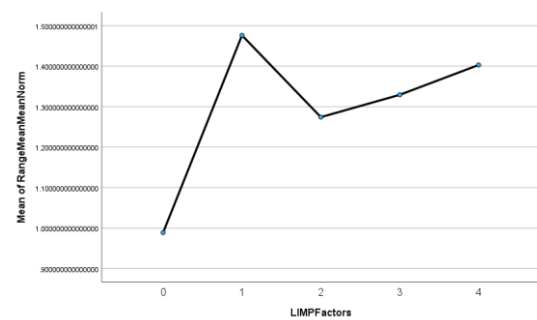


Figure 77: Means Plot of Anterior Tibial Translation (ATT) Range by LIMP Factor Levels. This visualization displays the average ATT Ratio RangeMeanMeanNorm for participants grouped according to the number of factors in their LIMP index.

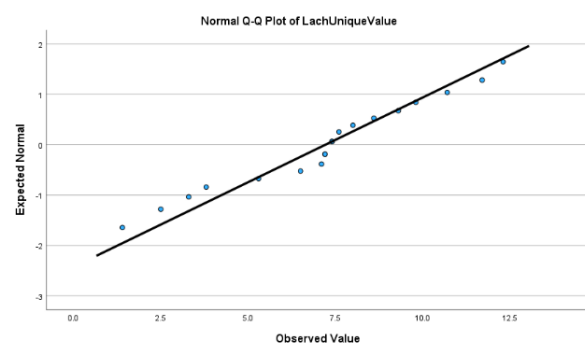
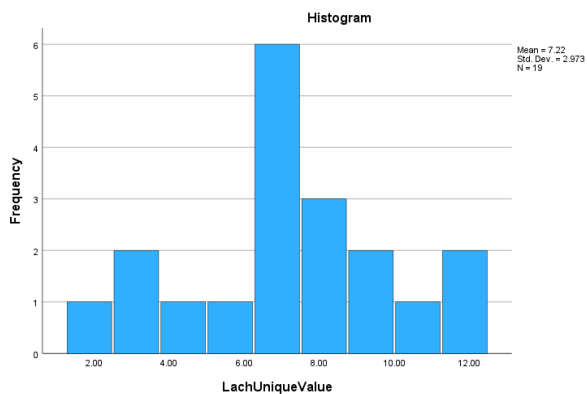


Figure 79: Histogram and Q-Q plot showing Graphical Distribution of Lachmeter readings for the Injured Cohort

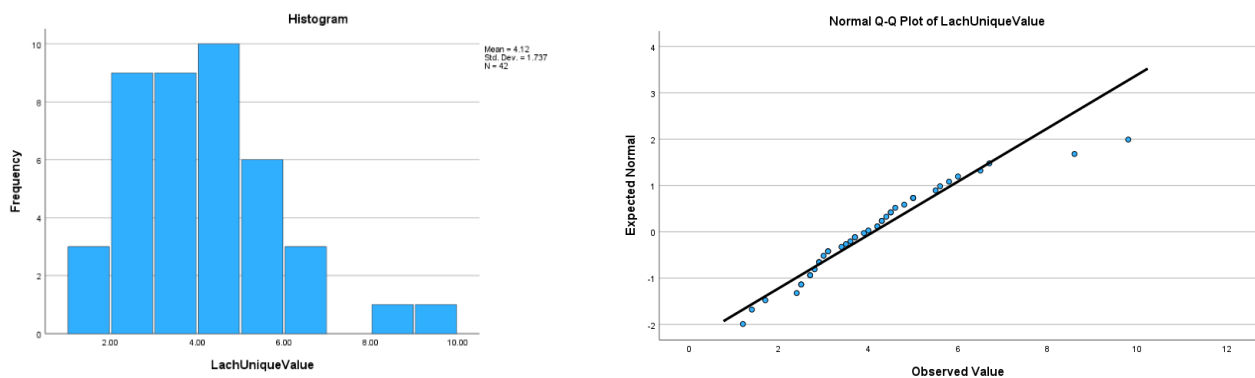


Figure 80: Histogram and Q-Q plot showing Graphical Distribution of Lachmeter readings for the Healthy Cohort

Table 70: Model Summary including -2 Log likelihood, Cox & Snell R Square, and Nagelkerke R Square, illustrating the model's goodness of fit and explanatory power for ACL injury diagnosis.

Model Summary			
Step	-2 Log likelihood	Cox & Snell R Square	Nagelkerke R Square
1	38.704 ^a	.159	.212
a. Estimation terminated at iteration number 4 because parameter estimates changed by less than .001.			

Table 71: Analysis of Variance (ANOVA) Examination of AMRL Ratio Among ACL-Injured Cohorts: Healthy Controls, ACL Injuries without MCL involvement, ACL with MCLs and ACL with MCLd.

ANOVA						
Ratio Type		Sum of Squares	df	Mean Square	F	Sig.
RangeMaxMaxNorm	Between Groups	2.153	3	.718	7.309	<.001
	Within Groups	3.437	35	.098		
	Total	5.591	38			
RangeMeanMeanNorm	Between Groups	2.107	3	.702	8.039	<.001
	Within Groups	3.057	35	.087		
	Total	5.164	38			

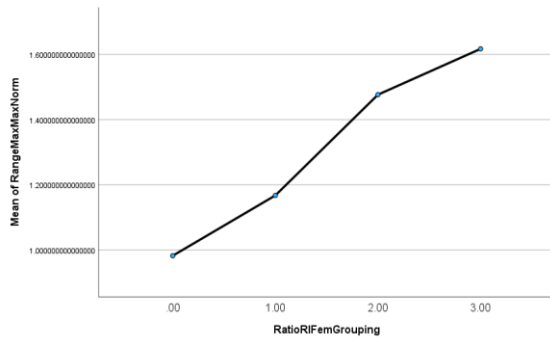


Figure 81: MaxMaxNorm Ratio of AMRL Means Plot for Injury Groupings

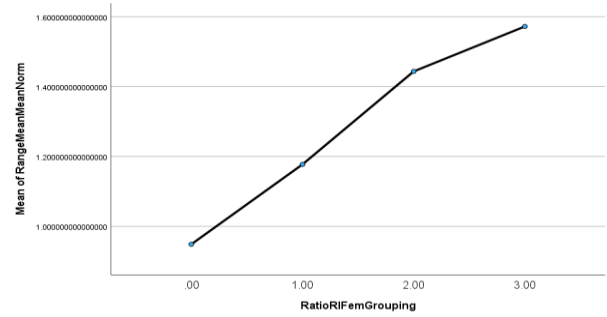


Figure 82: MeanMeanNorm Ratio of AMRL Means Plot for Injury Groupings

Table 72: Effect Sizes for ANOVA Analyses of Knee Laxity Measurements, including eta-squared, epsilon-squared, and omega-squared (for both fixed-effect and random-effect models) for the MazMaxNorm and MeanMeanNorm Ratios

ANOVA Effect Sizes ^a				
		Point Estimate	95% Confidence Interval	
			Lower	Upper
RangeMaxMaxNorm	Eta-squared	.385	.099	.537
	Epsilon-squared	.332	.022	.498
	Omega-squared Fixed-effect	.327	.021	.491
	Omega-squared Random-effect	.139	.007	.244
RangeMeanMeanNorm	Eta-squared	.408	.119	.556
	Epsilon-squared	.357	.043	.518
	Omega-squared Fixed-effect	.351	.042	.512
	Omega-squared Random-effect	.153	.015	.259

a. Eta-squared and Epsilon-squared are estimated based on the fixed-effect model.

Appendix E: EMG Analysis using a 3 S.D Threshold for Establishing Activation Threshold

Table 73: Percentage (%) of Participants Considered as Guarded for Each Muscle Group During the Respective Clinical Test

Test	Stratum	Percentage of Patients considered as being 'Activated' (%) 3 S.D		
		Quad	Ham	Gastro
AD Test	Injured	31.82	52.17	70
	Healthy	29.17	36.76	50
LM test	Injured	29.17	56	52.17
	Healthy	23.61	46.38	39.44
ADSOEOB Test	Injured	27.12	42.86	47.62
	Healthy	18.18	42.59	25.45

Table 74: Frequency of Participants Considered as Guarded and Not Guarded for Each Muscle Group During the Respective Clinical Test

Test	Stratum	Frequency of Patients considered as being 'Activated' (%) 3SD					
		Quadricep Activated	Quadricep Not Activated	Hamstring Activated	Hamstring Not Activated	Gastrocnemius Activated	Gastrocnemius Not Activated
AD Test	Injured	7	15	12	11	14	6
	Healthy	21	51	26	44	35	35
LM test	Injured	7	17	14	11	12	11
	Healthy	17	55	33	38	28	43
ADSOEOB Test	Injured	6	16	9	12	10	11
	Healthy	11	48	23	32	13	39

Table 75: Expected Frequencies of Participants Considered as Guarded and Not Guarded for Each Muscle Group During the Respective Clinical Test

Test	Stratum	Expected Frequencies of Patients considered as being 'Activated' (%) 3SD					
		Quadricep Activated	Quadricep Not Activated	Hamstring Activated	Hamstring Not Activated	Gastrocnemius Activated	Gastrocnemius Not Activated
AD Test	Injured	6.553	15.447	9.398	13.602	10.889	9.111
	Healthy	21.447	50.553	28.602	41.398	38.111	31.889
LM test	Injured	6	18	12.24	12.76	9.787	13.213
	Healthy	18	54	34.76	36.24	30.213	40.787
ADSOEOB Test	Injured	4.617	17.383	8.842	12.158	6.616	14.384
	Healthy	12.383	46.617	23.158	31.842	16.384	36.616

Table 76: Chi Squared Values and Associated Significance Levels to Evaluate the Differences in Guarding Between Stratum for Each Muscle Group During the Respective Clinical Test

Test	Stratum	Chi Squared and Significance Levels between Stratum					
		Quadricep Activated	Quadricep Not Activated	Hamstring Activated	Hamstring Not Activated	Gastrocnemius Activated	Gastrocnemius Not Activated
AD Test	Injured	Chi Square: 0.056		Chi Square: 1.62		Chi Square: 2.509	
	Healthy	P value: 0.8129		P Value: 0.2031		P Value: 0.1132	
LM test	Injured	Chi Square: 0.298		Chi Square: 0.671		Chi Square: 1.153	
	Healthy	P value: 0.5851		P Value: 0.4127		P Value: 0.2829	
ADSOEB test	Injured	Chi Square: 0.719		Chi Square: 0.007		Chi Square: 3.546	
		P Value: 0.3965		P Value: 0.9333		P Value: 0.0597	

Appendix F: Machine Learning Model Parameter breakdown

Machine learning models are comprised of hyperparameters, each have a different effect on handling the model data and subsequently the model's outputs. The effect of each hyperparameter is outlined below:

Number of Splits

The model uses a k-fold cross validation technique. The number of folds, otherwise known as 'splits' determines how the data is divided.

Each fold acts as a test set at some point, and as a part of the training set at other times. The model is trained on (k-1) folds, with the remaining fold used as the test set. This process is repeated k times, with each of the folds used exactly once as the test set. Hence, 'k' in k-fold cross-validation is the number of splits or partitions of the dataset. By training the model on multiple folds it increases the model's generalisability, increases real world applicability and decreases model bias, as each fold means different model exposure.

Down sampling factor

The down sampling factor reduces the number of data points inputted to the model. Down sampling reduces noise and means the model can generalise better as it ensures the model does not overfit to the data samples noise. However, increasing the down sampling factor by too much can mean subtle changes in the data are missed.

Batch size

The batch size defines the number of data samples processed before the models' internal parameters (weights and biases) are updated. The batch size is the number of training examples used to calculate the gradient of the loss function. The data asset is divided into several batches, each batch contains the specified number of data samples as per defined in the 'batch size'. The model processes each loss, computes the loss (a measure of prediction error), and then performs backpropagation to update the model weights in an attempt to reduce the loss.

Number and size of layers

The number and size of the layers changes the neural network's architecture. Each layer receives information from the previous layer and passes it onto the next, each layer contains a certain number of neurones. A neuron is a computational unit which takes one or more input and processes them and applies an activation function, this produces an output. The number of neurons in each layer determines the model's capacity or its ability to learn complex patterns in the data. More neurons can allow the network to learn more detailed features but can also lead to overfitting, where the model learns the training data too well, including the noise and errors, which can degrade its performance on unseen data.

Dropout Rate

The dropout rate is the probability of an input being excluded from a training update. E.g. a dropout rate of 0.2 would mean each neurone has a 20% chance of being dropped during training.

Learning Rate

The learning rate controls how much the weights of the model are updated, a higher learning rate means a more aggressive weight adjustment in each interaction and a smaller means more cautious adjustments.

Step Size – sub parameter of learning rate

The step size refers to how frequently the learning rate is updated.

Gamma – sub parameter of learning rate

Gamma is a factor used to reduce the learning rate according to a schedule, helping to fine-tune the training process.

Number of Epochs

The number of epochs is the number of times the entire data set is passed through the data set during training. The difference between epochs and iterations is that if the dataset has 1,000 samples and you use a batch size of 100, it takes 10 iterations to complete one epoch. Increasing the number of epochs allows the model to learn nuances in the data set but also increases the run time of the model.

Confidence Level

The confidence level is the threshold of whether the model prediction classifies a positive or negative result for a given rep.

Confidence Limit Participant

Confidence limits are introduced when multiple predictions are made for a single participant. i.e. where the data from multiple repetitions determines whether a participant is injured or healthy. It determines how confident the model needs to be across multiple repetitions to make decisions regarding the patient status. i.e. a value of 0.6 would mean at least 60% of the repetitions would need to be positive to dictate a positive participant outcome.

Included Axes

The included axes determine the data inputted into the model. This model includes 2 sensors, each have an X, Y and Z axis across an accelerometer and gyroscope.

Axes key:

The following are the axes codes for each trial.

- 0,1,2 -> acc femur (x,y,z)
- 3,4,5 -> gyro femur (x,y,z)
- 6,7,8 -> acc tibia (x,y,z)
- 9,10,11 -> gyro tibia (x,y,z)

I feel we need something on how these different components pull together to provide an output.

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