The Effect of Visual Reliance on Unplanned Change of Direction Biomechanics Following Anterior Cruciate Ligament Reconstruction

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The Effect of Visual Reliance on Unplanned Change of Direction Biomechanics Following Anterior Cruciate Ligament Reconstruction

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MSc Sports Physiotherapy & MSc High Performance Sport

Thesis Submitted for the Award of PhD

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Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of PhD is entirely my own work, and that I have exercised reasonable care to ensure that the work is original and have conformed to the regulations on the use and declaration of Generative AI, and does not to the best of my knowledge breach any copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work



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Abbreviations

ACL	Anterior cruciate ligament
ACLR	Anterior cruciate ligament reconstruction
AP	Anterior-Posterior
CI	Confidence interval
CoD	Change of direction
COM	Centre of mass
DM	Dominant
EEG	Electroencephalography
IC	Initial contact
JPS	Joint position sense
ML	Medial-lateral
MRI	Magnetic resonance imaging
NDM	Non-dominant
ROM	Range of motion
TTS	Time to stability
VR	Visual Reliance

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Publications

Journal Articles

I. Vitharana TN, King E, Moran K. Sensorimotor Dysfunction Following Anterior Cruciate Ligament Reconstruction- an Afferent Perspective: A Scoping Review. International Journal of Sports Physical Therapy. 2024 Jan 1;19(1):1410-1437. doi:10.26603/001c.90862.

II. Vitharana TN, King E, Welch N, Devitt B, Moran K. Sensorimotor Dysfunction Following Anterior Cruciate Ligament Injury (Part 1). What Is It? How Can Clinicians Assess It? Journal of Orthopaedic & Sports Physical Therapy. 2025 Jun;55(6):1-17. doi:10.2519/jospt.2025.12725

III. Vitharana TN, King E, Welch N, Devitt B, Moran K. Sensorimotor Dysfunction Following Anterior Cruciate Ligament Injury (Part 2): How Can Clinicians Rehabilitate It? Journal of Orthopaedic & Sports Physical Therapy. 2025 Jul;55(7):1-9. doi:10.2519/jospt.2025.12726.

Conference proceedings

I. Assessment and rehabilitation of sensorimotor dysfunction following ACLR. Sports Surgery Clinic, injury and peak performance in elite sport 2021, Dublin, Ireland.

II. ACLR rehabilitation and return to play- A sensorimotor perspective. Gaelic Games Association, player welfare conference 2024, Athlone, Ireland.

III. Visual-motor reliance following ACLR. UPMC Sports Surgery Clinic, orthopaedic and sports medicine conference 2024, Dublin, Ireland.

IV. A stepdown task that identifies visual reliance in ACL reconstructed athletes. Isokinetic, new frontiers 2025, Madrid, Spain.

V. ACLR rehabilitation- a sensorimotor perspective. Physiotherapy association of Latvia, annual conference 2025, Riga, Latvia.

Articles in submission

I. Vitharana TN, Welch N, Gorman B, Moran R, Moran C, Jackson M, Withers D, Devitt B, Moran K. Visual Reliance in Anterior Cruciate Ligament Reconstructed Athletes 8 Months Post-Surgery.

Articles awaiting submission

I. Vitharana TN, Moran R, Moran C, Jackson M, Withers D, Devitt B, Moran K. Visual Processing Abilities Do Not Differ between Anterior Cruciate Ligament Reconstructed Athletes 8 Months Post-Surgery and Healthy Controls.

II. Vitharana TN, Gorman B, Moran R, Moran C, Jackson M, Withers D, Devitt B, Moran K. The Effect of Visual Reliance on Unplanned Change of Direction Biomechanics in Anterior Cruciate Ligament Reconstructed Athletes 8 Months Post-Surgery.

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Abstract

Name: Thilina Vitharana

Title: The effect of visual reliance on unplanned change of direction biomechanics following anterior cruciate ligament reconstruction.

Introduction: Anterior cruciate ligament (ACL) injuries occur in sports requiring athletes to execute high intensity movements such as change of direction (CoD). Most ACL injuries are non-contact, suggesting movement technique and motor planning processes are the main injury drivers. ACL reconstruction (ACLR) is the main treatment but there remains a relatively high risk of reinjury when returning to sport. This may be due to motor planning centres becoming more reliant on visual information. This visual reliance (VR) may increase cognitive processing demands when executing CoD in chaotic sporting environments, resulting in errors in movement technique and increased ACLR reinjury risk. This thesis primarily aimed to examine whether VR affected the CoD biomechanics in ACLR athletes.

Methods: This thesis incorporates the work from six research questions (Chapters 3, 4, 5, 6, 7 and A) and a scoping review on afferent dysfunction (within Chapter 2). Reliability studies (Chapters 3, 5 and A) collected data from healthy controls utilising three-dimensional motion capture, force plate and visual processing software, whilst the cohort studies (Chapters 4, 6 and 7) collected data from two cohorts: ACLR and healthy controls.

Results: ACLR athletes demonstrated increased VR during a postural stability task on the ACLR limb as compared to their uninjured limb and a healthy control limb. No difference in visual processing abilities was noted between ACLR athletes and healthy controls. ACLR athletes with VR exhibited biomechanics that would be protective of future ACLR reinjury during an unplanned CoD task as compared to those without VR.

Conclusion: This thesis adds important insights into how VR can be assessed clinically and how it may influence unplanned CoD biomechanics. The methods explored can now be incorporated into rehabilitation and return to play testing to identify a subgroup within the ACLR population which may benefit from targeted rehabilitation.

Chapter 1

Introduction

Anterior cruciate ligament (ACL) injuries are unfortunately common amongst athletes participating in multi-directional sports (Boden et al., 2000). ACL reconstruction (ACLR) is the mainstay of treatment for individuals aiming to return to multi-directional sport. However, extensive rehabilitation (between six to twelve months) is required following an ACLR before an athlete is ready to return back to sport. Even after completing rehabilitation and returning to sport, athletes post-ACLR have a high rate of reinjury (Webster et al., 2014; Sandon et al., 2020). There has been little change in ACLR reinjury rates over the last 15 years (Shelbourne et al., 1995; Laboute et al., 2010; Sandon et al., 2020; Shelbourne et al., 2014) which potentially suggests that rehabilitation is not optimised and may be missing a component beyond the traditional focus on strength, power and sports-specific training (Davies et al., 2017; Meszler et al., 1998; Myklebust and Bahr, 2005; van Melick et al., 2016). Recent research has begun to focus on the changes that occur within the sensorimotor system and its effects on motor planning and execution following ACLR (Swanik, 2015) as a potential reason for the continued high reinjury rates.

All injuries occur when the rate and/or magnitude of loading exceeds the load tolerance of the tissue (Bertelsen et al., 2017). The majority of ACL injuries occur during non-contact, high velocity and high loading tasks such as change of direction (CoD) or landing from a jump (Boden et al., 2000). The non-contact nature of the injury suggests that an athlete's movement technique plays a significant role in determining the rate and magnitude of load placed on the ACL (Bertelsen et al., 2017). The sensorimotor system, which encompasses the sensory systems (e.g. somatosensory, visual, vestibular and auditory) and motor systems (e.g. descending motor system

and spinal reflexive system), plays a large role in how an athlete plans and executes a movement (Gibson, 1986; Goodale, 1998; Peterka, 2002). The sensorimotor system utilises the sensory systems, predominantly the somatosensory and visual systems, to gain an appreciation of the athlete's posture within the environment so that an appropriate movement technique can be employed by the motor system that is situation specific (Davids et al., 2012; Gibson, 1986). It has been suggested that a deficit in the one of the sensory systems, such as the somatosensory system, (directly damaged or adapted in response to injury) may result in the sensorimotor system increasing its reliance on the visual system (Grooms et al., 2015a), leading to increased neurocognitive demands during movement. As sport is often chaotic in nature, with an athlete being required to execute movements rapidly whilst making quick decisions, increased neurocognitive demands within the sensorimotor system may potentially lead to the athlete employing suboptimal movement techniques which may place excessive load on the ACL (Piskin et al., 2022; Gokeler et al., 2024).

The ACL is an important structure for the knee and holds two key roles: preventing excessive anterior tibial translation and providing afferent feedback to the sensorimotor system (Kosy and Mandalia, 2018; Park et al., 2005). Therefore, injury to the ACL can result in significant reductions to the stability, both structural and functional (Friel and Chu, 2013), of the knee which can lead to reduced sports participation (Cheecharern, 2018; Webster et al., 2019) and high risk of reinjury (Erickson et al., 2016; Sandon et al., 2020). Whilst ACLR restores the mechanical stability to the knee in the anterior-posterior direction, the return of afferent proprioceptive nerve endings has been found to be variable (Dhillon et al., 2012). Proprioceptive deficits (part of the somatosensory system) have been shown in elite athletes even after they have completed rehabilitation and returned to sport (Relph and Herrington, 2016b). It has been suggested that reduced information from the somatosensory system following ACL injury and subsequent ACLR, may lead to the sensorimotor system increasing its reliance on the visual system when planning and executing

movements (Grooms et al., 2015a). Several studies have demonstrated increased activity in the visual system of the brain during non-weightbearing knee flexion-extension tasks (via functional brain MRI) in ACLR participants as compared to healthy controls (Criss et al., 2020; Grooms et al., 2017; Lehmann et al., 2021a). However, although increased visual reliance has been demonstrated on functional brain MRI, no study to date has assessed whether visual reliance affects an athlete's movement technique. In addition, while it has also been postulated that visual reliance following ACLR may increase the risk of ACLR reinjury (Grooms et al., 2015a), to date it has only been demonstrated in one single-case study (Grooms et al., 2015c). The individual in the single-case study reinjured their ACL with a non-contact mechanism several days after a functional brain MRI which had shown greater cortical activation within the visual processing centres as compared to other matched ACLR individuals (Grooms et al., 2015c). Clearly, more research is required in this area to determine if visual reliance (VR) exists following ACLR, and whether it affects movement biomechanics in tasks that may place high loads on the ACL, such as CoD or jumping. Therefore, the overall purpose of this thesis is to examine whether VR following ACLR affects change of direction biomechanics.

In addressing this overall purpose, the following aims will be addressed:

1. Determine if VR can be identified via a clinical test.
2. Determine if VR affects unplanned CoD biomechanics in ACLR athletes.

Sub-Aims

1. Determine if visual processing abilities are different between ACLR athletes and controls.

These will be addressed across two themes, VR and visual processing (see Figure 1.1) in the following studies:

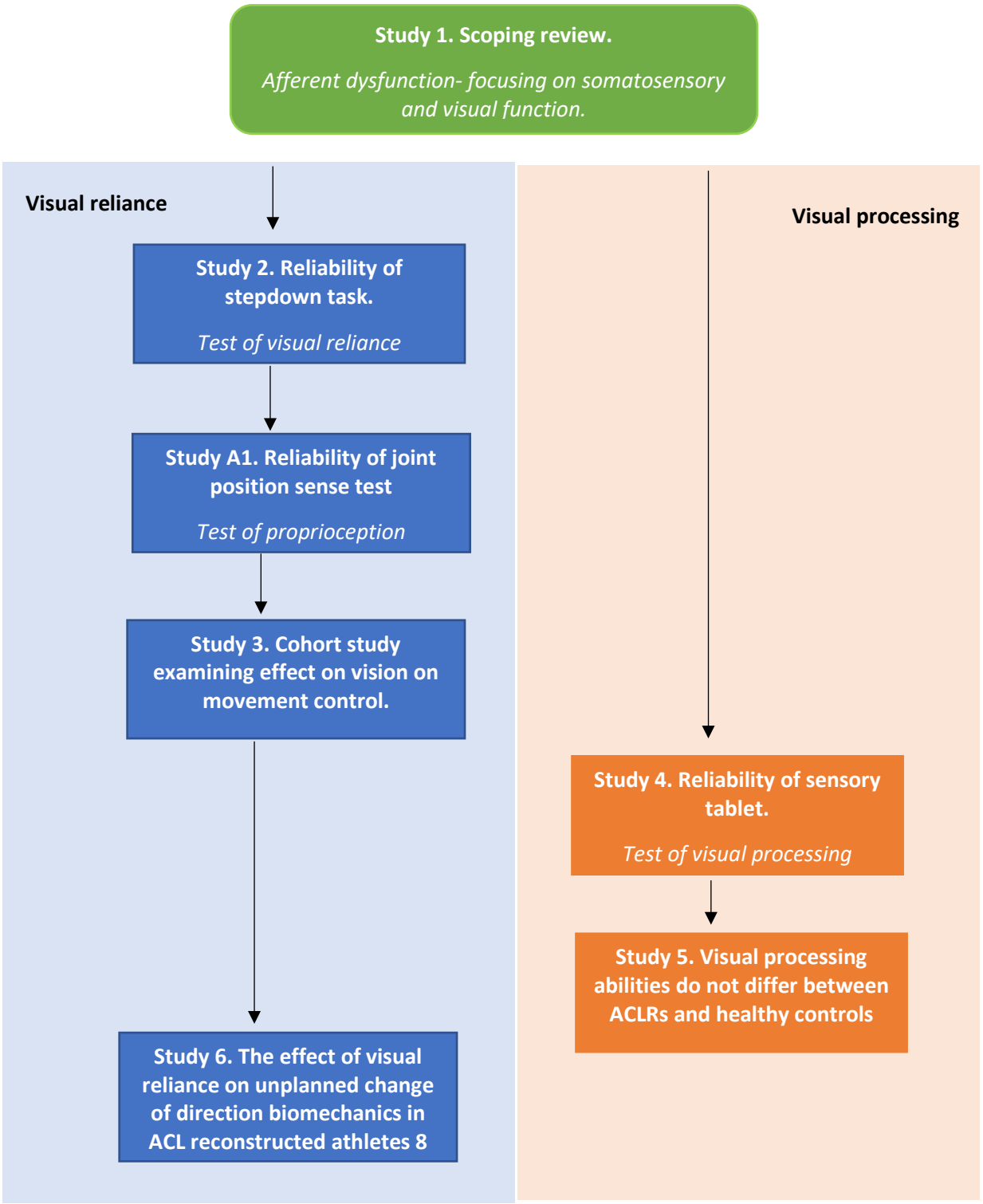


Figure 1.1 Flowchart to detail the structure of the PhD and the studies involved to address the aims and sub aims

Study 1 (within chapter 2)- Sensorimotor dysfunction following ACLR- an afferent perspective: a scoping review.

Sensorimotor dysfunction following an ACLR has been demonstrated to occur across all aspects of the system: afferent, efferent and central processing (Neto et al., 2019a; Gokeler et al., 2012; Grooms et al., 2017). It has been suggested that the efferent dysfunction following an ACLR is in response to the dysfunction created within the afferent system (Neto et al., 2019a). The afferent system encompasses a range of sensory systems such as somatosensory and vision. Within the somatosensory system, there are a number of sensations such as proprioception, kinaesthesia, vibration, touch and pain. Much of the research to date has focused on proprioception and kinaesthesia, whilst avoiding the other sensations. Also, the effect of ACLR on the visual system is a relatively new area of research. Therefore, the primary aim of this study was to review to all studies to date that examined the effect of ACLR on all aspects of somatosensory and visual dysfunction. The literature review was used to identify an appropriate joint position sense test to measure proprioception and identify gaps in the literature regarding the assessment of visual processing and VR.

The results from the scoping review have been published in the International Journal of Sports Physical Therapy: Sensorimotor dysfunction following ACLR- an afferent perspective: a scoping review (Vitharana et al., 2024).

Study 2 (Chapter 3)- The reliability of a stepdown task to assess for the weighting of visual information during a motor task.

VR following ACLR has previously been demonstrated in studies utilising functional brain MRI (Criss et al., 2020; Grooms et al., 2015a; Grooms et al., 2017; Grooms et al., 2015c). However, functional brain MRI is not freely available to most clinicians and therefore further research is required to identify clinical tests that may determine if an athlete has VR. Clinical testing to

identify VR currently focus on balance testing under varying visual conditions. The most common balance test used is single leg standing with full vision compared to when blinded (Kim et al., 2017b). The difference in performance under the two visual conditions determines how reliant an individual is on their vision (a worsening in balance performance when blinded suggests a degree of visual reliance). Although functional brain MRI demonstrates increased VR in the ACLR cohort, single leg balance testing fails to demonstrate this reliance when comparing ACLR cohorts to healthy controls (Wikstrom et al., 2017). This failure may be because the task, single leg balance, does not stress the motor control system enough. Therefore, a task that is higher loading may be needed to detect if an athlete is VR. A stepdown task with full vision, in which individuals are asked to step off a 20 centimetre step and then balance for 20 seconds has previously been shown to be reliable in the ACLR population for measuring time to stability (Colby et al., 1999). However, no study has completed the stepdown task with no vision. The primary aim of this study was to assess the reliability of a VR index score that is calculated by completing the stepdown task under two different visual conditions (full vision and blinded). The stepdown task was utilised for study 3 and 6 (chapter 4 and 7, respectively).

Study 3 (chapter 4)- Visual reliance in ACLR athletes 8 months post-surgery.

The ACL holds an important role in providing proprioceptive information to the motor control centres owing to its rich abundance of proprioceptive nerve endings (Johansson et al., 1991; Kosy and Mandalia, 2018). Injury and subsequent reconstruction of the ACL is believed to result in individuals becoming more reliant on their vision to plan and execute movements (Grooms et al., 2015a). The shift to VR, as evidenced via alterations in brain activity, occurs as early as six weeks post-surgery (Lehmann et al., 2021a) and has been demonstrated to continue to be present in those three to four years post-surgery (Criss et al., 2020). It is suggested that

those who are more VR are at greater risk of reinjury (Grooms et al., 2015c). However, previous research has focused on utilising functional brain MRI and electroencephalography to identify differences in brain activity and not how this change in brain activity may affect motor control (Grooms et al., 2017; Grooms et al., 2015c). As mentioned above (study 2), previous research utilising single leg balance tasks (eyes open versus eyes closed) has failed to identify VR in ACLR athletes. However, Study 2 also demonstrated that the VR index score derived from a stepdown task was a reliable measure. Therefore, the primary aim of this study was to determine if ACLR athletes are more VR as compared to a healthy control group, utilising the stepdown task, eight months post-surgery.

This study has been submitted for publication.

Study 4 (chapter 5)- The reliability of a sensory tablet in assessing visual processing abilities.

The visual system is an important sensory system involved in motor control (Sarlegna and Sainburg, 2009). If the visual system is damaged or becomes inefficient, then errors can occur in motor control. Reduced visual memory, reaction and visual processing speed amongst collegiate athletes is a risk factor for primary ACL injury (Swanik et al., 2007). Studies assessing visual processing abilities have utilised computer-based concussion software such as the 'Impact' (ImPACT, USA) and 'Cogstate' (Cogstate Ltd, USA) platforms (Swanik et al., 2007; Chaput et al., 2021a). It has been suggested that sensory stations that are able to assess across a number of visual processing abilities may be better able to identify deficits in visual processing. Therefore, the aim of this study was to examine the reliability of a tablet sensory station that assesses across seven visual processing abilities: visual clarity, contrast sensitivity, depth perception, visual memory, near-far quickness, multiple object tracking and reaction time. This tablet system was utilised for study 5 (chapter 6).

Study 5 (Chapter 6)- Do visual processing abilities differ between ACLRs and healthy controls?

Athletes need to make decisions and move within a chaotic environment. To effectively do so, they require good visual processing abilities so that they may assess their environment and their position within that environment (Goodale, 1998; Liu et al., 2020). Amongst college athletes, it has previously been shown that those with reduced reactions times, visual memory and processing speeds were more likely to rupture their ACL (Swanik et al., 2007). Similar research amongst the ACLR cohort has found mixed findings with some studies demonstrating significant reductions in gaze accuracy (Bodkin et al., 2021) and reaction times (Armitano-Lago et al., 2020), whilst other studies demonstrated no significant difference in other scales such as visual memory (Chaput et al., 2021a). The reason behind the mixed findings may be in part due to the heterogeneity in outcome measures used amongst the different studies and the small number of studies that have investigated this area. Therefore, the aim of this study was to determine if there were differences in visual processing abilities (contrast sensitivity, depth perception, multiple object racking, perception span and reaction time) between ACLR and healthy controls.

Study 6 (Chapter 7)- The effect of visual reliance on unplanned change of direction biomechanics in ACL reconstructed athletes 8 months post-surgery

ACL injuries predominantly occur in a non-contact fashion during high loading tasks such as CoD, decelerations or landings (Boden et al., 2000). This suggests that an athlete's movement technique plays a significant role in sustaining an ACL injury (Bertelsen et al., 2017; Boden et al., 2000). Movement technique is influenced by an athlete's physical capacities such as strength, power and reactive strength (Falch et al., 2020; McCormick et al., 2014). Outside of physical capacities, movement technique is influenced by the motor control centres. Errors within the motor control centres may result in suboptimal movement technique. VR following ACLR is

believed to result in altered and inefficient processing within the motor control centres which may lead to errors (Gokeler et al., 2019; Grooms et al., 2015c). Whilst VR is thought to increase the risk of ACLR reinjury due to the altered processing within the motor control centres (Grooms et al., 2015c), no study has examined how VR affects movement biomechanics in a CoD task. Therefore, the aim of this study was to examine if VR affects movement biomechanics in an unplanned CoD task in ACLR reconstructed athletes eight months post-surgery.

Chapter 2

Literature review

This review of literature focuses on the visual and somatosensory components of the sensorimotor system and the changes that occur following an anterior cruciate ligament reconstruction (ACLR). The influences of these changes on the execution of movements were also examined as well as the biomechanical factors during change of direction that are pertinent to ACLR reinjury.

It will show that dysfunction occurs within the visual and somatosensory systems following an ACLR and there is an increased reliance on the visual system. It will also show that currently, no study has examined whether visual reliance affects movement technique.

2.1 Anterior cruciate ligament anatomy

The anterior cruciate ligament (ACL) is the main static stabiliser against anterior translation of the tibia in relation to the femur (Markatos et al., 2013). It provides approximately 86% of resisting anterior translation force throughout all stage of knee motion (Markatos et al., 2013). It has a secondary stabiliser role to restrain external and internal rotation (Ball et al., 2020; Duthon et al., 2006). The ACL is comprised of two bundles (anteromedial and posterolateral) of highly organised type I collagen (Petersen and Zantop, 2007), with the posterolateral bundle providing greater resistance in knee extension as compared to the anteromedial bundle (Duthon et al., 2006). As the knee flexes, the anteromedial bundle becomes more taut and provides

greater resistance to anterior translation than the posteromedial bundle (Hollis et al., 1991). It is this complex anatomy that can make ACLR challenging. ACLR will either consist of a single or double bundle reconstruction (utilising either a hamstring tendon, patellar tendon or quadriceps tendon autograft) with the suggestion that double bundle may be superior as it allows better control of tibial rotation and anterior translation (Järvinen et al., 2012). However, double bundle reconstruction is more complex and patient reported outcomes after one and two years are no different to single bundle reconstruction (Das et al., 2023b). Hence, single bundle reconstruction is commonly performed as it provides similar resistance to anterior translation and potentially slightly reduced rotation stability (Goldsmith et al., 2013). The ACL is also richly innervated with proprioceptors (Dhillon et al., 2011; Morales-Avalos et al., 2024). The proprioceptors are involved in affecting knee postural changes as deformations within the ligament influence the output of muscle spindles in the hamstrings and quadriceps (Zimny et al., 1986; Duthon et al., 2006). Therefore, it is believed that the ACL plays a large role in knee proprioception to assist with joint stability and the planning and execution of movements (Banios et al., 2022; Riemann and Lephart, 2002c).

2.2 Mechanisms of ACL injury

A keen understanding of the mechanisms underpinning ACL injury is essential to help prevent primary injury and ACLR reinjury. ACL injury mechanisms are multifactorial which involve an interplay between neuromuscular, biomechanical, anatomical, genetic and hormonal factors (Shultz et al., 2015). ACL injuries have a mean incidence of approximately 0.06 per 1000 hours of athlete exposure (Pulici et al., 2023; Joseph et al., 2013) and are commonly encountered in field and court-based sports which require athletes to perform high velocity and high loading tasks such as changing direction, decelerating or landing (Martinez-Calderon et al., 2025). The rate of ACLR is high with Australians under 25 years having an a rate of 91 per 100,000 people (Zbrojkiewicz et al., 2018), which resulted in an estimated cost of AUD$142 million in 2014-15

(Zbrojkiewicz et al., 2018). A majority (70-88%) of ACL injuries occur either in a non-contact mechanism or indirect contact mechanism (contact to an area of the athlete other than the knee which perturbs their stability) to the knee (Boden et al., 2000; Della Villa et al., 2020). Situational patterns in sport also may play a role in non-contact ACL injuries with instances in football commonly occurring with defensive pressing action, tackling or being tackled (Sundberg et al., 2025). A common feature of limb position at the time of a non-contact injury is that the knee is often in a position between hyperextension and slight flexion (Boden et al., 2000), resulting in the ACL having greater tensile properties to resist anterior shear forces. Similarly, with the knee extended, a knee valgus movement of the knee can increase the loading on the ACL and subsequently lead to injury (Kacprzak et al., 2024). ACL injuries occur more frequently during match play as compared to training at almost 2:1, with football noting a greater proportion of match play injuries occurring in the first half of play which would suggest that fatigue may not be a significant driver of ACL injuries but rather intensity and neurocognitive demand (Sundberg et al., 2025; Della Villa et al., 2020).

Another consideration with non-contact ACL injuries is that it suggests that an athlete's movement technique and ability to maintain joint stability following perturbation are important factors when examining ACL injury. Whilst key determinants of movement technique are physical capacities (strength, explosive power and reactive strength) (Bertelsen et al., 2017), motor planning and execution processes are also large influences on movement technique (Swanik, 2015; Yeom et al., 2020). Therefore, when examining mechanisms of ACL injury, it is important to understand the movement technique they employed, and the underlying motor planning and execution processes.

2.3 Movement technique

Non-contact ACL injuries occur within 50-70 milliseconds of ground contact (Withrow et al., 2006; Bates et al., 2020). Non-contact ACL injuries typically occur during a sudden deceleration such as change of direction (CoD) and landing (Sundberg et al., 2025). Of the two movements, CoD tends to be the more prevalent injury mechanism (63-82%) in basketball (Gill et al., 2023) and football (Buckthorpe et al., 2024), and hence it is commonly assessed to determine an individual's risk of ACL injury during rehabilitation and return to play (RTP) testing. During CoD and landing tasks, there are common features that may increase the loading on the ACL and lead to injury; large knee extensor moment on an extended knee (Nunley et al., 2003; Dürselen et al., 1995), large knee valgus moment in conjunction with large knee extensor moment (Hewett et al., 2005) and increased resultant anterior shear force within the knee (Yu and Garrett, 2007; Dürselen et al., 1995; Shoemaker et al., 1993; Nunley et al., 2003; Markolf et al., 1995). Hence, a large focus on RTP testing following ACLR is spent on assessing technique-related biomechanical variables during CoD and landing.

2.4 Motor planning and execution processes

There is a growing body of literature examining whether inefficient motor planning and execution processes, as indirectly measured via poor neurocognitive performance or neurocognitive errors during movement, results in ACL injuries (Swanik, 2015; Gokeler et al., 2024; Buckthorpe et al., 2024). Dysfunction in these processes whilst in a chaotic sporting environment may lead to athletes erroneously employing suboptimal movement technique, which may potentially increasing the load on the ACL (Swanik, 2015). Increased burden on the motor planning centres may arise from poor visual memory, visual processing speeds and reaction times which have all previously been shown to be lower during baseline testing of athletes who subsequently sustained an ACL injury (Swanik et al., 2007). This is further supported by studies which analysed ACL injuries in professional soccer which showed approximately 78% of the non-

contact ACL injuries were related to errors in motor planning and execution due to incorrect shifting of visual attention, attentional error or making an incorrect pressing motion after being deceived by an opponent (Buckthorpe et al., 2024; Della Villa et al., 2020; Gokeler et al., 2024). Therefore, when assessing an athlete's movement technique during rehabilitation or RTP testing, unplanned or reactive tasks should be employed to challenge the athlete's motor planning and execution processes.

2.5 Sensorimotor system

The sensorimotor system is a complex system that incorporates the sensory systems, efferent systems and the integration of information that occurs centrally (Riemann and Lephart, 2002a). It is essential for joint stability, and to plan and execute movements (Riemann and Lephart, 2002c).

Afferent systems

The afferent systems are the sensory systems (somatosensory, visual, vestibular, auditory and gustation) which provide sensory information to the motor planning centres in the brain (Brooks and Cullen, 2019). The motor planning centres utilise this information to determine the body's posture within the environment and spatial-temporal features of the environment (Mirabella et al., 2008). Thereby allowing a motor response to be generated to achieve the desired goal.

The somatosensory system and visual systems are the most pertinent for movement (Vitharana et al., 2024; Vitharana et al., 2025a). The somatosensory system consists of fast and slow nerve fibres that carry information regarding, pain, pressure, touch and proprioception (Crawford and Caterina, 2019). These fibres carry information to the brain to provide an internal 'image' of the body's posture and also to the spinal cord for a quick reflexive response (such as pulling a limb away from a painful stimuli) (Dubin and Patapoutian, 2010). The visual system, on the other hand, entails the eyes and the optical pathways to the occipital lobe in the brain (Prasad and Galetta,

2011). Together, the somatosensory and visual systems provide the brain with a detailed representation of the surrounding environment and the body's posture within it (Corlett, 1992).

Efferent system

The efferent system involves the neural structures involved with transmitting information from the motor cortex in the brain to the target structures, such as muscle fibres (Catala and Kubis, 2013). Neurons travel from the motor cortex through the corticospinal tract within the spinal cord. From here, lower motor neurons then synapse with the descending neuron to transmit the information to the target muscle. This is how the motor planning centres can action a movement.

Reflexive responses allow for quick changes in muscle tone or quick muscle actions in response to an afferent stimulus (Héroux, 2017). This allows for quick action in response to pain or unanticipated perturbations to the body to protect the body from injury and maintain joint stability, respectively (Dietz et al., 1991). This is especially important during unplanned or reactive movements as there is greater unexpected perturbation to body segments which requires appropriate reflexive responses to maintain control and correct for any errors (Vlutters et al., 2018; Ferber et al., 2002; Riemann and Lephart, 2002a).

Central processing

Central processing of information from the afferent and efferent systems occurs within the brain. It requires the processing of sensory information (from the somatosensory and occipital lobes) and executive decision-making functions (working memory, cognitive flexibility and inhibition control) so that a movement strategy can be implemented (Zhuang et al., 2024; Edwards et al., 2019). This information is then processed within the motor lobe so that the appropriate muscles can be activated to execute the desired movement.

2.6 Planning and executing motor tasks

Planning and executing a jump or CoD task is complex, with the need to coordinate the many muscles and joints of the body to achieve the movement task (Cordo and Gurfinkel, 2004). The neurocognitive demands are increased when motor planning and execution is performed in a sporting situation due to the ever-changing complex environment with moving opponents, ball handling and gameplay tactics (Büchel et al., 2022; Taberner et al., 2025a). Ecological dynamics suggests that motor actions are the result of constant interactions between the athlete, environment and the task they are attempting to complete (Davids et al., 2012; Renshaw et al., 2022; Savelsbergh et al., 1999). This theory suggests that the athlete is constantly perceiving the environment and their place within it, via their somatosensory or visual systems, to inform how they execute their jumping or CoD tasks. However, a reduction in either the somatosensory or visual information due to injury has the potential to threaten the athlete's ability to perceive the environment or determine their posture within it and may lead to altered motor planning and execution.

For an athlete to complete a jump or CoD task in a sporting situation it is first and foremost determined by their physical capacities: strength, power and technique. This then interacts with the affordances provided by the environment (the space available to the individual and objects/opponents in that space) and the task to result in the eventual observed jump or CoD. Increased muscular strength and power have a positive relationship with CoD ability (Nimphius et al., 2010) and jumping performance (Rousanoglou et al., 2008). However, an athlete's technique for jumping and CoD is more complex with relation to the motor system. Motor tasks are executed either originating from the primary motor cortex or secondary motor cortices. Motor tasks executed by the primary motor cortex are under conscious control whilst tasks executed by the secondary motor cortices are more subconsciously controlled. Because athletes are

repeatedly executing CoD and jumping tasks, the neural circuitry to coordinate the muscle activation to perform these tasks will be found in the secondary motor cortices. This centrally generated technique will then be modified based of the environmental information provided by the sensory systems. An example of this would be an athlete in the middle of a football field will have subtle differences in their CoD technique in response to an opponent on natural grass field as opposed to artificial turf field (Strutzenberger et al., 2014). Of the five sensory systems: the somatosensory and visual systems are the most pertinent to gaining information from the environment to allow for effective motor planning and execution.

The somatosensory system provides afferent information regarding proprioception (awareness of joint position) and kinaesthesia (awareness of joint movement) (Vitharana et al., 2024). This allows the individual to gain a representation of how their body is placed within the environment. This information may play two roles during motor planning and execution. The first being to gain a representation of the individual's starting posture so that the appropriate motor units can be fired to achieve the motor task. The second role being to assess the final posture of the individual following the motor task to determine if it was successfully completed as planned. The visual system provides environmental information by continually scanning their visual field and tracking objects whilst they are moving.

Effective somatosensory and visual functioning is required for both planned and unplanned movements. Planned movements require greater contribution of the somatosensory and visual systems to provide information primarily towards feedforward mechanisms and secondarily for feedback corrections (Seidler et al., 2004). When completing a planned movement, select somatosensory cortical centres are activated prior to the movement to help improve movement control (Ariani et al., 2022). This is also evidenced via electromyography, in which the pre-anticipation of potential perturbations during the movement leads to greater pre-perturbation muscle activation to maintain control during a movement (Ruest et al., 2025). It has also been

found that when visual information regarding a target is shown early and then later removed during the movement, the participants are still able to reach a target accurately which suggests that the visual system has pre-informed the motor control centres of spatiotemporal information in a feedforward manner (Saunders and Knill, 2003). Feedback corrections are still required during a planned movement although its overall contribution to motor control in this situation is less than feedforward processes. Previous work has identified that long-latency reflexes utilise somatosensory inputs to correct limb movements (Pruszynski and Scott, 2012). However, when examining unplanned movements, which have been demonstrated to result in altered biomechanics as compared to planned movements (Brown et al., 2014; Ebner et al., 2025), there is reduced reliance on feedforward preparation due to the reduction in time to prepare a movement and a shift to greater reliance on fast sensorimotor integration (both somatosensory and visual) during feedback loops. This is evidenced in studies utilising perturbations which demonstrated increased cortical activation between the sensory and motor cortices (Jacobs and Horak, 2007), and rapid corrective reflex responses from both the somatosensory system (Crevecoeur and Kurtzer, 2018) and visual system (Day and Lyon, 2000).

The ACL is highly innervated with proprioceptor afferent fibres and injury to the ACL results in a loss of these nerve fibres (Dhillon et al., 2012). One of the goals of ACLR is to regain proprioceptive function by providing a graft that becomes the scaffolding for new afferent nerve fibres to grow into. However, the return of these proprioceptor fibres following ACL injury and subsequent ACLR is variable (Dhillon et al., 2012). Measures of proprioception (joint position sense and threshold to detect passive motion) have been shown to be significantly reduced in the ACLR limb as compared to both the uninjured limb and healthy control limbs even after individuals have completed rehabilitation and have returned to sport (Lehmann et al., 2017; Relph and Herrington, 2016b; Relph et al., 2014a). This reduction in function of the somatosensory system will result in a reduced ability for the individual to determine their posture within the environment, thereby potentially leading to an increased utilisation of the visual system to

account for this reduced postural information. This is shown with significantly poorer single leg postural control following ACLR when vision is obscured as opposed to when the vision is utilised for the task (Okuda et al., 2005).

It can be seen that both sensory systems provide information regarding the environment and the athlete's posture within that environment. ACL injury and subsequent ACLR leads to reduced information from the somatosensory system and can potentially lead to sensory confusion and an over-reliance on the visual system when planning and executing motor tasks. This section will explore the sequalae of ACL injury and ACLR on the somatosensory and visual system during motor planning and execution.

2.7 Effect of ACLR on proprioception and kinaesthesia

The knee is a highly innervated joint with varying afferent receptors to provide proprioceptive information to the somatosensory cortex (Nyland et al., 1994). As discussed above, proprioception is essential for individuals to determine their body's posture within the environment and facilitates appropriate motor planning. The ACL is one of the most highly innervated structures in the knee with mechanoreceptors to provide afferent proprioceptive information to the somatosensory cortex (Kennedy et al., 1982). The afferent proprioceptive information that it provides is transferred and processed at several centres: the spinal cord (for fast reflexive action), lower brain (involved with learning, planning and timing motor movements) and the primary somatosensory cortex (integrating joint and movement sense to coordinate voluntary motor actions)(Gomez-Barrena et al., 1996; Park et al., 2005). This sensory information is critical for an athlete performing high velocity and high loading manoeuvres, such as CoD and jumping, in an ever-changing sporting environment. It allows for the required advanced cognitive planning through feed-forward motor control and also has capacity for reflexive action to facilitate some corrective action if any potential errors in movement occur to potentially protect the ACL. Therefore, reduced proprioception as a result of injury may increase the neurocognitive

demands and reduce the confidence of an athlete when performing these high velocity manoeuvres. This may account for why there is some evidence that reduced proprioception following ACLR has been correlated with reduced self-reported function (Barrett, 1991b; Roberts et al., 1999).

ACL injury resulting in a complete loss of the ligament can have a significant effect on proprioception. Individuals with ACL deficiency (ACLD) have been shown to have significantly worse proprioception and postural control when compared to healthy controls (Wikstrom et al., 2017; Negahban et al., 2014; Dhillon et al., 2011). This is further evidenced via functional MRI which demonstrated a reduction in somatosensory activation in individuals with ACLD (Kapreli et al., 2009). ACLR aims not only to return mechanical stability to the joint but to also regain proprioceptive function. However, to date, the available evidence suggests that return of proprioceptive afferent fibres to the ACL graft and hence proprioceptive function is variable and can be affected by surgical technique (Kosy and Mandalia, 2018). ACLR that preserves the remanent stump of the injured ACL have been shown histologically to have a quicker return of afferent proprioceptive nerve fibres in comparison to when the stump is removed (Kosy and Mandalia, 2018). Surgical technique is beyond the scope of this thesis and a factor that cannot be affected by rehabilitation clinicians. However, future research investigating knee proprioception following ACLR should report whether the stump was resected in the participants.

Proprioception following ACLR has been investigated in two reviews, one including a meta-analysis. It has been consistently demonstrated proprioception is reduced following ACLR (Gokeler et al., 2012; Relph et al., 2014a). Two common measures of proprioception in the literature are joint position sense (JPS) and threshold to detect passive motion (TTDPM). A review (Gokeler et al., 2012) including eight studies (four investigating JPS and four investigating TTDPM) concluded that following ACLR the mean deficit between the ACLR limb and uninjured limb was 0.2° (SD 0.2) for TTDPM and 0.5° (SD 0.4) for JPS. This contrasted side-to-side differences in

healthy controls which was 0.1° (SD 0.1) for TTDPM and 0.1° (SD 0.1) for JPS. These findings were supported by another review with meta-analysis (Relph et al., 2014a) that demonstrated significant pooled differences between the ACLR limb and the uninjured limb in JPS (0.52°, $p<0.001$) but not in TTDM (0.02°, $p=0.91$). They also demonstrated significant differences between the ACLR and healthy control limbs in JPS (0.35°, $p=0.001$) and TTDPM (0.38°, $p=0.03$). Whilst both studies showed statistically significant reductions in proprioception, it is questionable whether changes in JPS and TTDPM of less than one degree are clinically meaningful. There is limited literature regarding a clinically meaningful difference for JPS and TTDPM measures with one study suggesting five degrees as the cut-off (Callaghan et al., 2002), but there is little consensus in the current body of literature. However, although the reduction in proprioception may not be clinically meaningful, it is still an important clinical measure to identify when an athlete's proprioceptive function is altered.

2.8 Effect of ACLR injury on balance

The simple act of standing still upright is inherently an unstable position which requires balance- the integration of sensory information (somatosensory, visual and vestibular) to detect deviations from the desired orientation so that corrections can be made (Forbes et al., 2018; Ivanenko and Gurfinkel, 2018a). An athlete's ability to integrate sensory information for balance is especially important when high loading and high velocity manoeuvres such as CoD or jumping are performed. A recent systematic review demonstrated that the inclusion of balance training within injury risk reduction programs significantly reduced the incidence of ACL injury, thereby suggesting that poor balance may be a factor in increasing the risk of ACL injury (Su et al., 2025). However, currently there is a no prospective or retrospective research investigating the link between balance and ACLR reinjury, and prospective research into primary ACL injury is conflicting.

A number of clinical guidelines recommend the inclusion of balance exercises to prevent primary ACL injury and also to be utilised for rehabilitation following an ACLR (Petushek et al., 2019). However, much of the research utilised for these recommendations are based on prospective research utilising neuromuscular training/prevention programs which involve a combination of balance, strength, plyometric and sports-specific skill development. Therefore, it is difficult to determine the contribution that balance training itself has on reducing ACL injury risk. A systematic review (Hewett et al., 2006) demonstrated contrasting evidence (two prospective cohort studies) for balance training alone on reducing the risk of ACL injury, with one study (Caraffa et al., 1996) in elite male soccer players showing reduced ACL injuries in the intervention group whilst the other study (Soderman et al., 2000) in female soccer players showed no difference. Therefore, reduced balance may be associated with an increased risk of ACL injury, but more research is needed in this area to determine if it is a risk factor and to also determine thresholds for what would be categorised as good balance.

The ACL is one of the most highly innervated structures in the knee and provides somatosensory information to the central cortex (Kennedy et al., 1982). It therefore plays an important role in providing sensory information to be used in conjunction other sources of somatosensory and visual information to allow an athlete to maintain their balance. Following an ACL injury and subsequent ACLR, there is a change in the afferent somatosensory information arising from the ACL graft resulting in diminished activation of sensorimotor cortical regions and increased activation of secondary somatosensory and visual cortical areas (Grooms et al., 2017; Kapreli et al., 2009). This remapping of the sensory cortical areas may result in reduced balance.

To date there has been one systematic review which examined ten studies regarding balance during static and dynamic tasks in those who had undergone an ACLR and healthy controls (Howells et al., 2011). The review found that although there was a trend for improved balance in the control group during static tasks, it did not reach significance. Four studies included in the

review examined more dynamic tasks, such as involving unstable surfaces or perturbations, with mixed findings. Two of the studies demonstrated that those with ACLR had significantly reduced balance as compared to healthy controls. However, due to the small number of studies and the small sample size in these studies, the results need to be interpreted with caution. This potentially suggests that as the balance demands increase on the athlete, the ACLR-induced sensorimotor changes and the visual system are unable to integrate sensory information appropriately to account for the demands. An issue with the current assessment of balance in the evidence presented is that the task is conducted with the athletes standing stationary. However, an athlete returning to sport following ACLR is required to perform high velocity and high loading tasks, such as CoD and jumping, which place greater demands on their balance than the standing tasks used for the review. Therefore, future research may need to look to challenge an athlete's balance ability in higher loading tasks to determine if there are differences between ACLR and healthy controls.

2.9 Visual reliance post-ACLR

As mentioned previously in this section, effective motor planning and execution relies on the interaction between the athlete and the environment (Renshaw et al., 2022). This requires an athlete to have an accurate internal representation of their body's posture and the environment they are in. This becomes especially important when athletes are required to perform high velocity and high loading tasks in a sporting context in which there are opponents and potential multi-task requirements such as handling a ball. The visual system is one of the sensory systems utilised by the athlete to both gain a representation of the environment and also to be used in conjunction with the other sensory systems to understand their body's posture within that space (Chaudhary et al., 2022).

The visual system encompasses the eyes and the occipital lobe in which the sensory information is interpreted and integrated with other information so that conscious decisions can be made (Prasad and Galetta, 2011). It has been suggested that the visual system may be the predominant sensory system utilised during planning and execution of motor tasks (Goodale, 1998; Duchowski, 2017; Stein and Glickstein, 1992), such that when there is conflict between afferent information provided by the somatosensory system and that of the visual system, then the visual information will take precedence when planning a motor response (Stein and Glickstein, 1992; Patla, 1997). There are a couple of conflicting theories as to the how that information is interpreted but the common thread between them is that information from the visual system provides the central cortex with information regarding what is in the environment and where it is (Duchowski, 2017). This then assists in the creation of an appropriate motor response once integrated with other sensory information. Injury to one of the sensory systems likely results in increased demands on the other sensory systems and increased central processing demands to account for the gap in information when deciding on an appropriate motor response (Grooms et al., 2015a).

The ACL is a highly innervated structure in the knee which provides somatosensory information to the central cortex. As discussed in the previous section, following ACL injury and subsequent ACLR there is altered afferent somatosensory input. Functional brain MRI studies have shown that following ACLR, there is increased activity in the visual processing cortices (Nyland et al., 2017; Grooms et al., 2017). This was also coupled with an overall increased activity in the secondary somatosensory cortices (involved with the processing of painful stimuli and motor control) during the simple task of non-weightbearing knee flexion/extension (Grooms et al., 2017). Although there is a lack of research in this area, it suggests that ACLR can lead to altered somatosensory functioning and a re-weighting of the sensory systems to increased reliance on the visual system for motor planning and execution. This re-weighting potentially reflects an increased cognitive demand during motor activities which may be detrimental to an athlete who is required to react to a changing environment and execute jumping or CoD tasks.

An increased reliance on the visual system and increased cognitive demands with motor planning and execution have been suggested as potential reasons for ACL injury (Grooms et al., 2015c). Two prospective studies (Swanik et al., 2007; Grooms et al., 2015c): one a large cohort study and the other a case study have demonstrated that increased neurocognitive demands have an increased risk of ACL injury. The prospective cohort study involved college athletes performing computer-based neurocognitive testing and found that athletes were significantly more likely to sustain a non-contact primary ACL injury if they had slower reaction times (Cohen *d*= 0.46), slower processing speed (Cohen *d*= -0.55), worse visual memory (Cohen *d*= -0.77) and worse verbal memory (Cohen *d*= -0.47) (Swanik et al., 2007). Although, this suggests that those with poorer cognitive abilities in these domains are at greater risk of injury, it is difficult to determine whether this is because the groups have biomechanical technique differences during high risk tasks like jumping and CoD. A case study utilising functional brain MRI demonstrated that an athlete who reinjured their ACL 26 days following the scan had increased activity of visual-motor, motor planning and sensory processing cortical areas in comparison to a matched ACLR participant (Grooms et al., 2015c). Again however, there is no reporting on any biomechanical or balance information, so it is difficult to determine the exact mechanism by which the increased neurocognitive demands and increased VR lead to ACL injury.

Performing high loading and high velocity tasks like CoD or landing requires the ability to integrate sensory information to coordinate their body within the environment they find themselves in. Altered somatosensory input following an ACLR can lead to VR and increased cognitive demands which may potentially lead to ACLR reinjury. Research to date has focused on identifying VR utilising specialist tools, such as functional brain MRI (Chaput et al., 2021a; Grooms et al., 2017) and electroencephalography (Lehmann et al., 2021a) to identify brain activity during simple movements. During simple knee flexion and extension tasks, increased activity in the visual processing centres has been reported in ACLR athletes as compared to controls (Grooms et al., 2017). However, a gap in the current literature is how this increased visual activity affects

biomechanical technique. Also, testing methods to identify VR that is more accessible to clinicians is currently lacking.

2.10 Effect of visual reliance on biomechanics

Whilst VR has been shown on functional brain MRI (Grooms et al., 2015c; Kapreli et al., 2009), there have been no studies to investigate the effect of VR on knee biomechanics. Due to the gap in the literature, the potential result of VR on biomechanics may need to be extrapolated from literature involving the effects of vision on knee biomechanics. A single systematic review (Louw et al., 2015) has been published in this area with mixed findings reported across the six studies included. In the review, only two studies (Santello et al., 2001; Chu et al., 2012) examined the effect of vision on double-leg drop landing biomechanics in healthy control and found significantly increased initial vertical ground reaction force when they performed the task with no vision as compared to full vision. There were conflicting findings regarding knee flexion angle at initial contact, with one study showing a significant increase in knee flexion angle (Santello et al., 2001) whilst the other showed a significant decrease (Chu et al., 2012). These mixed changes may be reflective of the participants adopting a cautious approach to landing due to no visual information of the environment and hence a greater reliance on somatosensory information. Whilst more research is required, especially in the ACLR population, a combination of increased vertical ground reaction force with altered sagittal knee kinematics may lead to increased loading on the ACL as explained in section 2.13 (Ogasawara et al., 2024). A study (Grooms et al., 2018) investigating the effect of altered vision during a drop vertical jump in ACLR participants demonstrated a significant increase in knee flexion during landing as compared to healthy controls, but there was no significant difference in other kinematic or kinetic measures. The ACLR group landed with an average of 4° greater knee flexion than healthy controls which may not be

clinically meaningful but highlights a potential reliance on the visual system in this population during a drop land.

In summary, the studies examining knee biomechanics with vision and with vision occluded demonstrated mixed findings with sagittal knee kinematics varying. Two of the three studies (Santello et al., 2001; Grooms et al., 2018) demonstrated increased knee flexion on landing which would suggest that a more protective strategy was employed. Increased vertical ground reaction force during a drop landing task when vision was occluded may mean that a stiffening strategy may have been employed in the absence of visual input and this may increase the loading on the ACL (Chu et al., 2012; Santello et al., 2001). These results may be extrapolated with caution to suggest that visual reliance may in some cases lead to a protective strategy being employed in some cases and not others. Caution is needed due to the small number of studies examined in this section and no study directly assessing visual reliance and knee biomechanics.

2.11 Effect of ACLR on efferent system

ACLR results in persistent changes to the efferent system as indirectly evidenced by long-term quadriceps atrophy (Thomas et al., 2016; White et al., 2024) and weakness (Hagen et al., 2025; Ingersoll et al., 2008). Changes in the efferent system have been noted both with regards to central processing (Neto et al., 2019a; Sylvester et al., 2025), descending corticospinal pathway (Sherman et al., 2025) and more peripherally at the muscle interface (Pietrosimone et al., 2015b).

Following an ACLR, the resulting pain and altered information within the afferent system results in the efferent system responding by increased inhibition within the motor lobe (Neto et al., 2019a). This, in conjunction with reduce spinal reflexive excitability (Lepley et al., 2014; Pietrosimone et al., 2015b), results in a reduced ability to recruit muscles and therefore may alter movement strategies. The chronic inhibition within the efferent system leads to structural changes in neural

pathways as evidenced by a smaller volume in the descending corticospinal tract (Lepley et al., 2020), and results in persistent weakness in the lower limb muscles (Yu et al., 2025). This may account for altered movement strategies identified between ACLR and healthy controls (Palmieri-Smith and Lepley, 2015; Ithurburn et al., 2021).

2.12 Scoping review: Sensorimotor dysfunction following anterior cruciate ligament reconstruction- an afferent perspective

The following study was published in full:

Vitharana TN, King E, Moran K. Sensorimotor Dysfunction Following Anterior Cruciate Ligament Reconstruction- an Afferent Perspective: A Scoping Review. *International Journal of Sports Physical Therapy*. 2024 Jan 1;19(1):1410-1437. doi: 10.26603/001c.90862.

It is presented in this section with only minor formatting changes to conform to this thesis

2.12.1 Abstract

Background

Sensorimotor dysfunction is thought to occur following anterior cruciate ligament (ACL) injury which may have implications on future reinjury risk. Dysfunction has been demonstrated within the efferent component of the sensorimotor system. However, no reviews have examined the two main components of the afferent system: the visual and somatosensory systems.

Hypothesis/Purpose

This study aimed to report differences in function (central processing and local processing) within the (1) somatosensory and (2) visual systems between individuals following anterior cruciate ligament reconstruction (ACLR) and healthy controls (between-subject). The study also aimed to report differences in function within the two systems between the two limbs of an individual following ACLR (within-subject).

Study Design

Scoping review

Methods

A search was conducted in PubMed, SPORTDiscus, CINAHL, Medline and Embase up until September 2021. Level I-IV studies assessing somatosensory and visual systems were included if they compared ACLR limbs to the uninjured contralateral limb (within-subject) or a healthy control limb (between-group). The function of somatosensory and visual systems was assessed across both central processing (processing of information in the central cortex) and local processing (all other assessments outside of central processing of information).

Results

Seventy studies were identified (52 somatosensory, 18 visual). Studies examining somatosensory central processing demonstrated significant differences; 66% of studies exhibited within-subject differences and 100% of the studies exhibited between-group differences. Studies examining local somatosensory processing had mixed findings; 40% of the 'joint position sense (JPS)' and 'threshold to detect motion (TTDM)' studies showed significant within-subject differences (JPS=0.8°-3.8° and TTDPM=0.2°-1.4°) and 42% demonstrated significant between-group differences (JPS=0.4°-5° and TTDPM=0.3°-2.8°). Eighty-three percent of visual central processing

studies demonstrated significant dysfunction between-groups with no studies assessing within-subject differences. Fifty percent of the studies examining local visual processing demonstrated a significant between-group difference.

Conclusion

Significant differences in central processing exist within somatosensory and visual systems following ACLR. There is mixed evidence regarding local somatosensory and visual processing. Increased compensation by the visual system and local visual processing dysfunction may occur in conjunction with somatosensory dysfunction.

Key Terms

Anterior cruciate ligament, sensorimotor dysfunction, visual reliance and afferent dysfunction

2.12.2 Introduction

The sensorimotor system is complex and a central element of the body's motor control system (Wolpert et al., 1998; Riemann and Lephart, 2002c; Riemann and Lephart, 2002a). It assists with the planning and execution of movement, and maintaining postural control (Figure 2.12.2.A) (Riemann and Lephart, 2002a). It encompasses afferent sensory pathways, efferent motor pathways and central cortex processing (Figure 2.12.2.B). Sensorimotor functioning is required for every movement; requiring integration of sensory information (in particular somatosensory and visual information) to detect deviations from desired orientations and to subsequently alter motor responses (Bizzi and Ajemian, 2020). Given that movement control requires sensorimotor function, as the complexity of movement increases, for example responding to more stimuli in the environment and/or utilising more multiplanar joint actions or muscles, the sensorimotor demands also increase (Gálvez-García et al., 2018). Therefore, sensorimotor dysfunction, which can occur following musculoskeletal injury (such as anterior

cruciate ligament [ACL] injury), may negatively affect movement planning and execution (Grooms et al., 2015a; Herman et al., 2015).

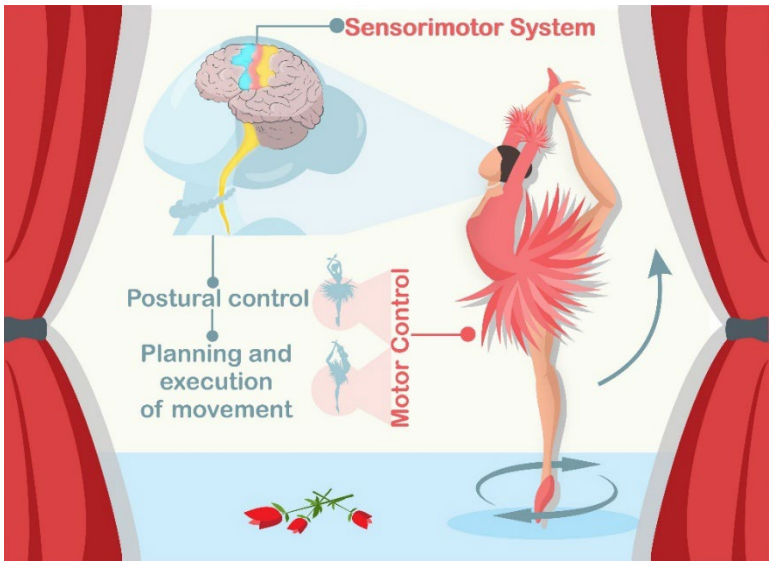


Figure 2.12.2.A. Sensorimotor cortex influences an individual's motor control

The ACL provides: (1) structural stability through limiting excessive tibia anterior translation and internal rotation (Dargel et al., 2007; Shin et al., 2009) and (2) sensory information to the sensorimotor cortex (Gomez-Barrena et al., 1996; Park et al., 2005). Therefore, ACL injury has negative consequences for knee structural stability (Yang et al., 2018; Sanders et al., 2017) and sensorimotor system functions (such as postural control, muscle coordination and supplying afferent information to the central cortex) (Williams et al., 2004; Lysholm et al., 1998; Courtney et al., 2005). Despite ACL reconstructive surgery (ACLR) restoring structural stability (Kannus and Järvinen, 1987; Paschos and Howell, 2017; Fithian et al., 2005; Swanik, 2015; Grooms et al., 2017), there is growing debate to whether sensorimotor dysfunction remains. Sensorimotor dysfunction following ACLR occurs across afferent sensory, central processing and efferent motor pathways (Pietrosimone et al., 2012; Pietrosimone et al., 2015b; Neto et al., 2019a). Recent reviews have reported dysfunction of the efferent pathways (Lisee et al., 2019; Hart et al., 2010; Neto et al.,

2019a) and certain aspects of that somatosensory system (proprioception and kinaesthesia) (Relph et al., 2014b; Gokeler et al., 2012). Whilst there are six sensory systems within the afferent system (somatosensory, visual, auditory, vestibular, gustation and olfactory), the somatosensory and visual systems are the most important for motor control (Hamill et al., 2020; Grooms et al., 2015a) and will be reviewed here.

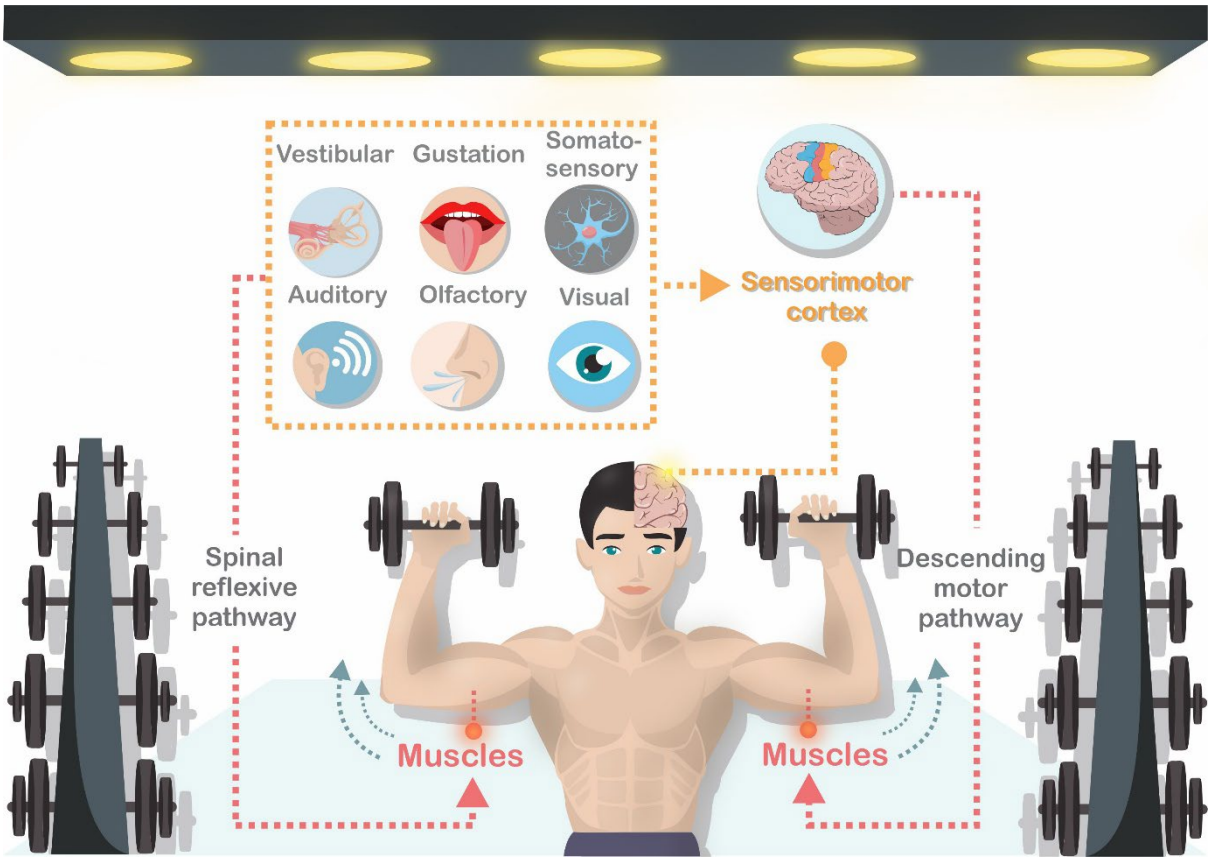


Figure 2.12.2.B Components of the sensorimotor system

The somatosensory system has several important functions, including: (1) informing the central cortex about segment position (proprioception) and movement (kinaesthesia), (2) sensing pain and pressure/vibration, and (3) sensing objects in the environment via touch (Puce and Carey, 2010). The ACL is highly innervated with mechanoreceptors that send proprioceptive afferent

information for processing to the spinal cord, lower brain and cerebrum (Gomez-Barrena et al., 1996; Park et al., 2005). A full-thickness ACL tear results in disruption of the mechanoreceptor mediated pathway (Dhillon et al., 2012), pain and swelling, thereby driving arthrogenic muscle inhibition (Hopkins and Christopher, 2000; Palmieri et al., 2004). Whilst two systematic reviews have investigated proprioception deficits (one domain of the somatosensory system), which highlighted significant but small functional reductions following ACLR (Relph et al., 2014b; Gokeler et al., 2012), no study has reviewed the other somatosensory system domains (e.g. central processing and vibration).

The visual system encompasses the eyes, optical neural pathways and the occipital lobe (where processing of the visual information occurs). It has several key functions, including helping to identify objects and providing object spatial location and orientation within their environment (Wade and Jones, 1997). Following the loss of ACL proprioceptive information, postural control is reduced with increased demands placed on motor planning centres within the brain. In particular, an over-reliance on the visual system can occur following ACLR and may contribute to ACL reinjury (Grooms et al., 2015b). While early research into visual system dysfunction was based on functional brain MRI (Grooms et al., 2015b; Kapreli et al., 2009), there is a small but growing body of research examining how processing visual information affects motor control (dual-task loading) following ACLR (Bodkin et al., 2021; Stone et al., 2018).

Given that efferent deficits have been reviewed comprehensively, a review examining afferent dysfunction following ACLR, and how it is measured, would help clinicians better assess and effectively target those deficits. Synthesising data from studies assessing ACLR somatosensory and visual system dysfunction is challenging due to the lack of studies and variety of outcome measures used, this paper therefore undertakes a scoping review to map key concepts and identify knowledge gaps (Peters et al., 2015; Peters et al., 2021).

2.12.3 Methods

The PRISMA guidelines for systematic reviews were followed with appropriate modifications for a scoping review (Page et al., 2021).

Research Questions

The original research question was separated into three:

1. What differences exist within the somatosensory system between both ACLR and healthy controls, and between limbs in the ACLR population?
2. What differences exist within the visual system between both ACLR and healthy controls, and between limbs in the ACLR population?
3. What tests are used to measure the somatosensory and visual systems differences between ACLR and healthy controls?

Eligibility

The inclusion criteria for studies in the scoping review were: (1) at least one outcome measure which assessed somatosensory or visual sensory performance, (2) included subjects post ACLR, (3) published in English, and (4) full-text access. The studies could be of any design (Peters et al., 2021; Peters et al., 2015).

Participants

Studies needed participants with unilateral ACLR. Participants were not excluded if they had concomitant knee injuries that required repair (such as meniscal damage). No restrictions were placed on ACLR technique or time from surgery. Participants were excluded if they had undergone a revision ACLR.

Search Strategy

An electronic search was conducted in PubMed, SPORTDiscus, CINAHL, Medline and Embase in September 2021 (Figure 2.12.3.A and 2.12.3.B). No restrictions were placed on the

date of publication. Two independent reviewers (TV and EK) conducted. The search related to the somatosensory system was ("ACLR" OR "ACL reconstruction" OR “anterior cruciate ligament reconstruction”) AND ("somatosensory" OR "proprioception" OR "somatosensation")). The search related to the visual system was (“ACLR” OR “ACL reconstruction” OR “anterior cruciate ligament reconstruction”) AND (“visual” OR “visual-motor”).

Study Identification

The two reviewers (TV and EK) independently reviewed the titles and abstracts of the identified studies. If a study matched the eligibility criteria, the full text manuscripts were subsequently reviewed independently. The full reference list of identified studies was searched to locate relevant studies. Studies were downloaded to EndNote reference manager (https://www.endnote.com) and imported into Covidence software (www.covidence.org) to identify potential differences between reviewers and to reach agreement regarding study eligibility. Disagreements were resolved via discussion or third-party mediation (KM).

Data Extraction

Data were extracted by each reviewer (TV and EK) for all eligible studies, entered into spreadsheets, and combined. Disagreements were resolved via discussion or third-party mediation (KM). The standardised data extraction forms included details on the study design, participant details (age, time after surgery, surgical technique and percentage of the cohort being males), outcome measures, and results. To help with clarity of interpreting the results, the studies were sub-grouped based on the outcome measures utilised. For the somatosensory system results, studies were separated into those which assessed for central processing differences and those which assessed local somatosensory functions. The central processing studies were those that assessed for brain activity during tasks, which allows for interpretation of how information is

processed in the central cortex. Local somatosensory functions were separated into studies that examined: proprioception (joint position sense), kinaesthesia (threshold to detect motion) and other somatosensory functions (such as light touch and vibration). With regards to the visual system results, the studies were grouped into three categories: central processing, local visual function and visual contribution to motor control. Central processing are those studies assessing how information is processed within the central cortex. Local visual function encompasses studies which utilised outcome measures that assessed visual functions, such as gaze tracking, visual memory and visual attention. Finally, studies were grouped into 'visual contribution to motor control' if their outcome measures assessed motor control during varying degrees of vision (to determine visual contribution) or with dual-cognitive tasks.

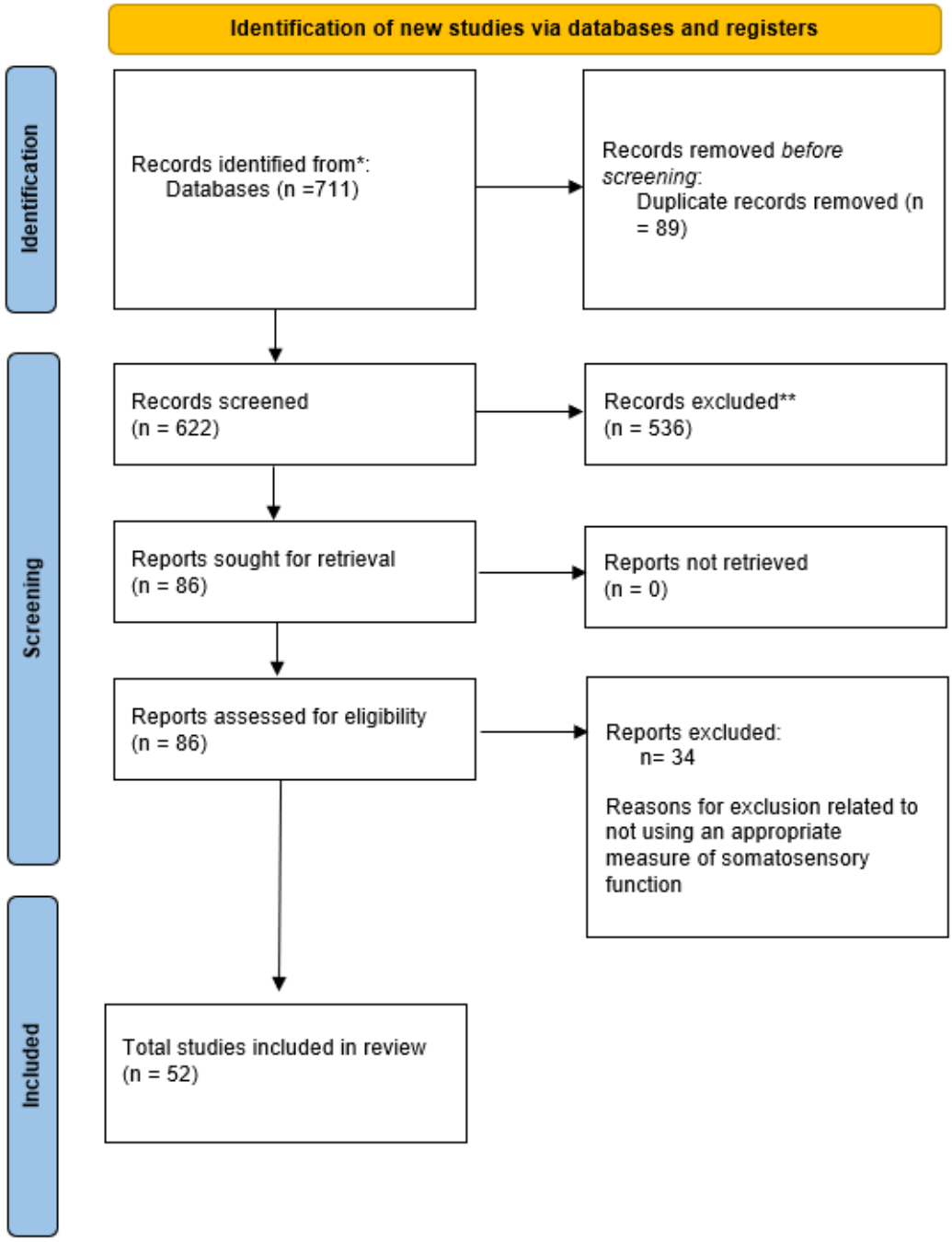


Figure 2.12.3.A. Flowchart of the search strategy and results of the somatosensory system

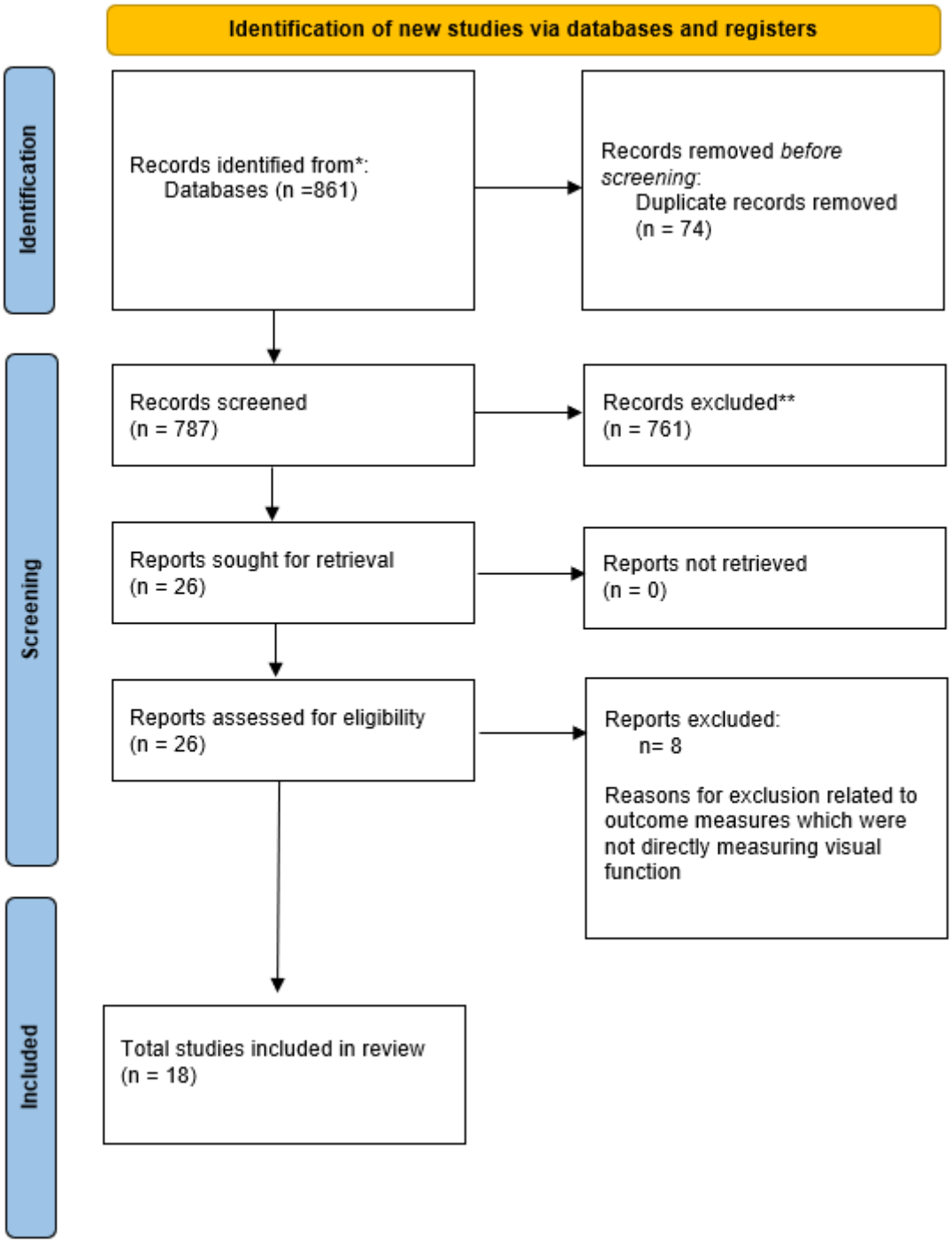


Figure 2.12.3.B. Flowchart of the search strategy and results of the visual system

2.12.4 Results

Outcome Measures

Seventy studies were included in the scoping review. There was large heterogeneity of the outcome measures, so to assist readers the measures and their purpose are listed in table 2.12.4.A (somatosensory system) and table 3 (visual system).

Table 2.12.4.A. Outcome measures utilised to assess the somatosensory system

Outcome measure	What it measures	Purpose of assessment
Electroencephalogram (EEG)	Measures electrical activity within the brain. Used to highlight brain areas responsible for processing specific information.	Used to identify central processing differences.
Functional brain MRI	Measures changes in blood flow within the brain which occurs with brain activity. Used to highlight brain areas responsible for processing specific information.	Used to identify central processing differences.
Vibration perception threshold testing	Used to identify the lowest vibrational intensity that the individual is able to perceive.	Differences between limbs at sites around the knee would suggest local functional deficiencies. Differences between limbs at sites distal to the knee (e.g. around the foot) would suggest central processing deficiencies.
Light touch perception threshold testing	Used to identify the lowest touch pressure intensity that the individual is able to perceive.	Differences between limbs at sites around the knee would suggest local functional deficiencies. Differences between limbs at sites distal to the knee (e.g. around the foot) would suggest central processing deficiencies.
Posturography	Used to measure an individual's postural control during upright standing under varying conditions (static or dynamic)	Used to identify central processing differences.
Joint position sense	Used to measure an individual's ability to perceive the position of their joints without utilising their vision.	Identifies differences in local function related to proprioceptive information

Threshold to detect passive motion	Used to measure an individual's ability to detect motion of their joint without utilising their vision.	Identifies differences in local function related to kinaesthetic information

Somatosensory System

Fifty-two studies (see Tables 2.12.4.B, 2.12.4.C and 2.12.4.D) were identified which assessed somatosensory function following ACLR. Nine studies examined central processing within the somatosensory system, whilst 44 examined local somatosensory functions (e.g proprioception, kinaesthesia and vibration). Some studies examined differences between the uninjured limb and ACLR limb (within-subject differences) (Table D1 in Appendix D) whilst others compared the ACLR limb to a healthy control's limb (between-group differences) (Table D2 in Appendix D). Several papers examined both between-group and within-subject differences.

Central processing of somatosensory information

Of the nine studies that examined cortical processing, there was heterogeneity in the assessment methods: three studies utilised electroencephalogram (EEG), one utilised functional brain MRI, two utilised vibration perception threshold testing, two utilised posturography and one utilised light touch threshold detection testing. Whilst these techniques assess central processing, there are slight differences in the information obtained. EEG and functional brain MRI assess brain activity during simple motor tasks, with increased activity reflecting somatosensory dysfunction due to greater processing requirements. Posturography assesses postural control under varying circumstances to determine afferent system efficacy (e.g. vestibular, visual, somatosensory). Finally, vibration and light touch perception threshold testing examine central processing changes by comparing thresholds at sites local and distal to an injury. Increased perception thresholds at sites distal to the injury indicate central processing changes.

Six studies examined ACLR within-subject differences with the majority (4/6) demonstrating significant differences in somatosensory central processing (reduction in function) (An et al., 2019; Bartels et al., 2018; Bartels et al., 2019; Courtney et al., 2019; Valeriani et al., 1999; Blackburn et al., 2020). Two studies found increased EEG activity (An et al., 2019; Valeriani et al., 1999), and two posturography studies demonstrated reduced somatosensory function in the ACLR limb (Bartels et al., 2018; Bartels et al., 2019). However, both studies examining vibration perception threshold demonstrated no significant difference between limbs (Courtney et al., 2019; Blackburn et al., 2020). Overall, studies suggest there are differences in central processing within the somatosensory systems in the ACLR limb, and vibration perception threshold may not be an appropriate method when examining ACLR within-subject differences.

Five studies examined somatosensory system central processing between ACLR participants and healthy controls, with all demonstrating significant differences (Grooms et al., 2017; An et al., 2019; Courtney et al., 2019; Hoch et al., 2017; Baumeister et al., 2008). One study demonstrated increased vibration perception threshold in the ACLR limb both locally (around the knee) and globally compared to healthy controls (Courtney et al., 2019). This study also demonstrated the uninjured limb of ACLR participants had increased vibration perception thresholds compared to healthy control limbs, further highlighting differences in the central processing of somatosensory information following ACLR. This was also reflected in a case control study (Hoch et al., 2017) in which light touch sensation at sites distal to the ACLR knee (medial malleolus and first metatarsal) was reduced as compared to healthy controls. The other two studies (EEG (An et al., 2019) and functional brain MRI (Grooms et al., 2017)) demonstrated increased somatosensory central cortex activity during simple motor tasks (non-weightbearing knee flexion and extension) compared to healthy controls.

Overall, following an ACLR, there are consistent differences in somatosensory system central processing. Not only does the ACLR limb have altered central processing as compared to the uninjured limb, but also as compared to healthy controls.

Table 2.12.4.B. Number and distribution of studies examining the somatosensory system. Listed underneath is the testing tool used in the identified studies

Domain	**Within-subject studies**	**Between-group studies**
Central processing	6 • EEG= 2 (Valeriani et al., 1999; An et al., 2019) • Posturography= 2 (Bartels et al., 2019; Bartels et al., 2018) • Vibration perception threshold= 2 (Courtney et al., 2019; Blackburn et al., 2020)	5 • EEG= 2 (An et al., 2019; Baumeister et al., 2008) • Functional MRI= 1(Grooms et al., 2017)Light touch perception threshold= 1 (Hoch et al., 2017) • Vibration perception threshold= 1 (Courtney et al., 2019)
Joint position sense	27 • Continuous passive motion device= 1 (Bonfim et al., 2003) • Custom built apparatus= 4 (Fremerey et al., 2001; Co et al., 1993; Fremerey et al., 2000; Fischer-Rasmussen and Jensen, 2000) • Electrogoniometer= 6 (Dvir et al., 1988; Anders et al., 2008; Büyükafşar et al., 2020; Suner Keklik et al., 2021; Hoshiba et al., 2020; Blackburn et al., 2020) • Image calculated angulation software= 5 (Relph and Herrington, 2016a; Silva et al., 2012; Mir et al., 2008; Hopper et al., 2003; Furlanetto et al., 2016) • Isokinetic dynamometer= 11 (Reider et al., 2003; Ghaderi et al., 2020; Jurevičienė et al., 2012; Kaya et al., 2019; Zult et al., 2018; Nagai et al., 2018; Angoules et al., 2011a; Ozenci et al., 2007; Karasel et al., 2010; Co et al., 1993; An et al., 2015)	25 • Continuous passive motion device= 1 (Bonfim et al., 2003) • Custom built apparatus= 4 (Fischer-Rasmussen and Jensen, 2000; Co et al., 1993; Barrett, 1991a; Armitano-Lago et al., 2020) • Electrogoniometer= 5 (Suner Keklik et al., 2021; San Martín-Mohr et al., 2018; Goetschius et al., 2013; Büyükafşar et al., 2020; Hoshiba et al., 2020) • Image calculated angulation software= 5 (Relph and Herrington, 2016a; Silva et al., 2012; Mir et al., 2008; Furlanetto et al., 2016; Strong et al., 2021) • Isokinetic dynamometer= 10 (Moezy et al., 2008; Ozenci et al., 2007; Nagai et al., 2018; Ordahan et al., 2015; Littmann et al., 2012; Chaput et al., 2021b; Guney-Deniz et al., 2020; Zandiyeh et al., 2019; Zhou et al., 2008; Baumeister et al., 2008)

Threshold to detect passive motion	16 • Continuous passive motion device= 1 (Bonfim et al., 2003) • Custom built apparatus= 7 (Valeriani et al., 1999; Muaidi et al., 2009; Risberg et al., 1999; Co et al., 1993; Fischer-Rasmussen and Jensen, 2000; MacDonald et al., 1996; Courtney et al., 2019) • Isokinetic dynamometer= 7 (Shidahara et al., 2011; Laboute et al., 2019; Nagai et al., 2013; Reider et al., 2003; Angoules et al., 2011a; Ozenci et al., 2007; Risberg et al., 2007a)	13 • Continuous passive motion device= 1 (Bonfim et al., 2003) • Custom built apparatus= 7 (Courtney et al., 2019; Co et al., 1993; Risberg et al., 1999; Fischer-Rasmussen and Jensen, 2000; MacDonald et al., 1996; Muaidi et al., 2009; Roberts et al., 2000) • Isokinetic dynamometer= 4 (Laboute et al., 2019; Zandiyeh et al., 2019; Ozenci et al., 2007; Reider et al., 2003)
Vibration	1 • Vibration perception threshold= 1 (Courtney et al., 2019)	2 • Vibration perception threshold= 2 (Courtney et al., 2019; Blackburn et al., 2020)

Abbreviations: EEG= electroencephalogram and MRI= magnetic resonance imaging

Local somatosensory function

Fifty studies examined various afferent pathways of somatosensory function: proprioception (joint position sense [JPS]), kinaesthesia (threshold to detect passive motion [TTDPM]) and vibration. The two most common were JPS and TTDPM, with large heterogeneity in the methods (Table 2).

Joint position sense

Twenty-seven studies examined within-subject JPS function (Table 2.12.4.C & Table 2.12.4.D). Across the 27 studies a total of 35 outcomes were measured due to JPS being measured

at multiple angles in some studies. Overall, there was mixed evidence with 13 studies demonstrating reduced JPS function in the ACLR limb, 20 demonstrating no significant difference and two demonstrating improved JPS function. Participant demographics and time from surgery did not differ between studies with and without a difference. Time from surgery was quite varied across studies, ranging from 4 to 52.2 months. Of the studies that demonstrated a significant reduction in JPS function within-subject, the difference between the two limbs ranged from 0.8° to 3.8° (Relph and Herrington, 2016a; Fischer-Rasmussen and Jensen, 2000; Fremerey et al., 2000).

Twenty-five studies examined JPS function between the ACLR limb and healthy controls (Table 2.12.4.C & Table 2.12.4.D). Across the 25 studies a total of 30 outcomes were measured due to JPS being measured at multiple angles in some studies. Similar to the within-subject studies, there were mixed findings, with 13 studies demonstrating significantly reduced JPS function in the ACLR group, 16 studies finding no significant difference and only one reporting improved JPS function in ACLRs (Strong et al., 2021). Of the studies that demonstrated a significant reduction in JPS function between ACLR limbs and healthy controls, the JPS difference between limbs ranged from 0.4° to 5° (Büyükafşar et al., 2020; Relph and Herrington, 2016a; Goetschius et al., 2013).

The small differences and the similar number of papers identifying JPS performance as being negatively affected as those reporting no difference for both between-group and within-subject differences, highlights the difficulty in measuring this variable. However, with almost 50% of the identified studies demonstrating reduction in proprioceptive function, JPS should be routinely assessed in ACLRs post-surgery. The small differences between-group and within-subject makes it difficult for clinicians to reliably monitor changes over time. Also, large heterogeneity in outcome measures and lack of reporting of the standard error of measurement makes it hard to draw firm conclusions. Future research should report the reliability and standard error of measurement

values for the outcome measures utilised to help readers and clinicians interpret the findings better.

Threshold to detect passive motion (TTDPM)

Seventeen studies examined within-subject TTDPM performance (Table 2.12.4.C & Table 2.12.4.D), with mixed findings. Across the 17 studies a total of 20 outcomes were reported due to some studies having multiple outcome measures. Nine studies reported reduced ACLR limb TTDPM (from 0.2° to 1.4°) (Fischer-Rasmussen and Jensen, 2000; Courtney et al., 2019), whilst eleven studies demonstrated no significant difference.

Thirteen studies examined TTDPM performance between the ACLR limb and healthy controls (Table 2.12.4.C & Table 2.12.4.D), with again mixed findings. Five studies reported significantly reduced ACLR limb function, whilst seven studies reported no significant difference. One study reported significantly better ACLR function. Of the studies that demonstrated a significant reduction in TTDPM performance between ACLR limbs and healthy controls, the JPS difference between limbs ranged from 0.3° to 2.8° (Courtney et al., 2019; Laboute et al., 2019).

Akin to JPS studies, a similar number of papers for both between-group and within-subject differences identified TTDPM performance as being negatively affected as those reporting no significant difference. In addition, the differences are also small. This may suggest that TTDPM is a function that should be routinely assessed in ACLRs as it may be negatively affected but that it is a variable that would be hard for clinicians to monitor for recovery due to the small magnitude in the differences. Also, there is large heterogeneity in testing methodology with limited reporting on standard error of measurement for each outcome measure which makes firm conclusions difficult.

Other afferent components of local somatosensory function

Other measures of somatosensory function can include vibration perception threshold testing (of local sites around the knee). However, only two studies examined this, with conflicting findings. Courtney and colleagues (2019) found significantly greater perception thresholds in the ACLR limb compared with both the uninjured limb and healthy controls, while Blackburn and colleagues (2020) reported no significant difference between the ACLR limb and the uninjured limb. Greater vibration perception thresholds around the knee can indicate local negative changes within the somatosensory system. The lack of research in this area makes it difficult to make firm conclusions regarding the potential effect of ACLR on this somatosensory function.

Table 2.12.4.C Studies examining within-subject differences (ACLR limb versus uninjured limb) in the somatosensory system.

Somatosensory level	**Studies reporting significantly decreased function in ACLR group (p<0.05)**	**Studies reporting no significant difference**	**Studies reporting significantly increased function in the ACLR group (p<0.05)**
Proprioception (JPS)	(Anders et al., 2008) (Angoules et al., 2011b) (Bonfim et al., 2003) (Büyükafşar et al., 2020) (Fischer-Rasmussen and Jensen, 2000) (Fremerey et al., 2001) (Fremerey et al., 2000) (Ghaderi et al., 2020) (Hoshiba et al., 2020) (Jurevičienė et al., 2012) (Relph et al., 2014b) (Relph and Herrington, 2016b) (Silva et al., 2012)	(An et al., 2015) (Anders et al., 2008) (Angoules et al., 2011b) (Blackburn et al., 2020) (Büyükafşar et al., 2020) (Co et al., 1993) (Dvir et al., 1988) (Fischer-Rasmussen and Jensen, 2000) (Fremerey et al., 2001) (Furlanetto et al., 2016) (Hopper et al., 2003) (Hoshiba et al., 2020) (Karasel et al., 2010) (Kaya et al., 2019) (Mir et al., 2008) (Nagai et al., 2013) (Ozenci et al., 2007) (Reider et al., 2003)	(Dvir et al., 1988) (Reider et al., 2003)

		(Suner Keklik et al., 2021) (Zult et al., 2018)	
Kinaesthesia (TTDPM)	(Angoules et al., 2011b) (Bonfim et al., 2003) (Co et al., 1993) (Courtney et al., 2019) (Fischer-Rasmussen and Jensen, 2000) (Laboute et al., 2019) (MacDonald et al., 1996) (Nagai et al., 2013) (Valeriani et al., 1999)	(Angoules et al., 2011b) (Laboute et al., 2019) (Muaidi et al., 2009) (Nagai et al., 2013) (Ordahan et al., 2015) (Ozenci et al., 2007) (Reider et al., 2003) (Relph et al., 2014b) (Risberg et al., 1999) (Risberg et al., 2007a) (Shidahara et al., 2011)	
Vibration	(Courtney et al., 2019)	(Blackburn et al., 2020) (Courtney et al., 2019)	

Table 2.12.4.D. Studies examining between group differences (ACLR limb versus healthy controls

Somatosensory level	**Studies reporting significantly decreased function in ACLR group (p<0.05)**	**Studies reporting no significant difference**	**Studies reporting significantly increased function in the ACLR group (p<0.05)**
Proprioception (JPS)	(Barrett, 1991b) (Baumeister et al., 2008) (Bonfim et al., 2003) (Büyükafşar et al., 2020) (Fischer-Rasmussen and Jensen, 2000) (Goetschius et al., 2013) (Guney-Deniz et al., 2020) (Relph et al., 2014b) (Relph and Herrington, 2016a) (San Martín-Mohr et al., 2018) (Silva et al., 2012)	(Armitano-Lago et al., 2020) (Büyükafşar et al., 2020) (Chaput et al., 2021a) (Co et al., 1993) (Fischer-Rasmussen and Jensen, 2000) (Furlanetto et al., 2016) (Goetschius et al., 2013) (Guney-Deniz et al., 2020) (Hoshiba et al., 2020) (Littmann et al., 2012) (Mir et al., 2008) (Ordahan et al., 2015)	(Reider et al., 2003)

	(Suner Keklik et al., 2021) (Zhou et al., 2008)	(Ozenci et al., 2007) (San Martín-Mohr et al., 2018) (Strong et al., 2021) (Zandiyeh et al., 2019)	
Kinaesthesia (TTDPM)	(Courtney et al., 2019) (Laboute et al., 2019) (Relph et al., 2014b) (Roberts et al., 2000) (Zandiyeh et al., 2019)	(Bonfim et al., 2003) (Fischer-Rasmussen and Jensen, 2000) (MacDonald et al., 1996) (Muaidi et al., 2009) (Reider et al., 2003) (Ozenci et al., 2007) (Risberg et al., 1999)	(Co et al., 1993)
Vibration	(Courtney et al., 2019)		

Visual System Results

Eighteen studies (see Table 2.12.4.F) assessed visual system differences following ACLR. Across the 18 studies a total of 20 outcomes were reported due to some studies having multiple outcomes measures. Fifteen studies examined differences between ACLR participants and healthy controls, whilst five studies examined differences between limbs in the ACLR participants. The studies identified assessed specific visual processes (both local and central) and/or the contribution of the visual system during motor control.

Central processing

Six studies (Giesche et al., 2021; Chaput et al., 2021b; Criss et al., 2020; Grooms et al., 2017; Grooms et al., 2015b; Lehmann et al., 2021b) assessed differences in visual system central processing between ACLR participants and healthy controls. No studies assessed within-subject differences in the ACLR population. Five of the six studies (Lehmann et al., 2021b; Grooms et al., 2017; Grooms et al., 2015b; Chaput et al., 2021b; Criss et al., 2020) demonstrated increased

activity in visual processing regions of the brain, via either functional brain MRI or EEG, in ACLR participants during simple movements (Z-max scores of greater than 4). Increased activity may be a sign of compensation with regards to altered somatosensory information or a sign of dysfunction within the visual system (Kapreli et al., 2009; Neto et al., 2019a). These studies were completed over a large time range post-surgery (1.5 ± 0.2 months (Lehmann et al., 2021b) to 43.3 ± 33.3 months (Criss et al., 2020)). This may indicate that differences in visual processing activity are persistent and may develop quite early post-surgery. The remaining study demonstrated no significant difference (Giesche et al., 2021). Various visual processing areas within the brain have been identified as areas of greater activity within the ACLR population. Grooms and colleagues (Grooms et al., 2017) demonstrated significantly greater activation of the lingual gyrus, which is responsible for visual processing and visual memory, suggesting a compensatory mechanism for reduced somatosensory information described earlier (somatosensory results). The results from Criss and colleagues (2020) further supports this. They found increased activation of regions responsible for visual processing and combined visuospatial perception and attention.

Overall, there are differences in ACLR visual system central processing. It is unknown if these differences are present prior to ACLR or if it is a result of ACLR. Future prospective studies (assessment pre-ACL injury and then post-ACLR) are required to determine this.

Local visual function

Six studies examined local visual function differences between ACLR participants and healthy controls with conflicting results (Stone et al., 2018; Chaput et al., 2021b; Bodkin et al., 2021; Roelofsen et al., 2020; Armitano-Lago et al., 2020). One study (Stone et al., 2018) assessed local visual function with multiple outcome measures, so there is some overlapping of results. There are numerous methods to assessing local visual function including computer-based visual memory tasks (Chaput et al., 2021b), gaze tracking (Bodkin et al., 2021) and measuring reaction

times to visual stimuli (Stone et al., 2018) (Table 3). Three studies (Roelofsen et al., 2020; Armitano-Lago et al., 2020; Bodkin et al., 2021) demonstrated ACLR significantly reduced local visual function (related to gaze tracking of multiple objects, visual attention and reaction to visual stimulus), three studies (Stone et al., 2018; Chaput et al., 2021b; Bodkin et al., 2021) demonstrated no significant difference (related to visual memory, gaze tracking stationary object and reaction time to visual stimulus), and one study (Stone et al., 2018) demonstrated ACLR improved function (related to visual attention) . The contrasting findings may be due, at least in part, to the large heterogeneity in outcome measures (Table 2.12.4.E). Some studies utilised neurocognitive tests to assess visual attention (the ability to select specific objects in the environment and filter out the irrelevant information) and visual memory (the ability to store and recall visual information (Chaput et al., 2021b), whilst others utilised tests to assess the qualities of vision such as gaze tracking (ability to track objects in the environment) (Bodkin et al., 2021) and reactions to visual stimulus (Stone et al., 2018; Armitano-Lago et al., 2020; Roelofsen et al., 2020). Bodkin and colleagues (2021) found that their ACLR group had large differences (Cohen d= 0.96) when tasked with tracking a moving object, resulting in a greater number of visual gaze errors, but no differences when focusing on a stationary object. This contrasting finding has significant relevance when playing sport. ACLR are also slower to react to visual information and adjust their posture accordingly (Armitano-Lago et al., 2020). With the majority of ACL injuries being non-contact in nature and heavily influenced by movement strategy (Boden et al., 2000; Bertelsen et al., 2017), the changes to visual information processing in ACLRs may influence their motor strategy with consequences for performance and re-injury susceptibility.

Only one study (Roelofsen et al., 2020) assessed within-subject differences in local visual function demonstrated reduced function. Roelofsen and colleagues (2020) assessed the effect of visual feedback on leg amplitude movement during a visual tracking task. They demonstrated that ACLRs had significantly decreased leg amplitude in response to visual feedback in comparison to not only healthy controls but also to their limb prior to surgery. This result may indicate that there

are changes in the way visual information is processed but they may also be the result of reduced proprioception.

Table 2.12.4.E. Outcome measures utilised to assess the visual system

Outcome measure	**What it measures**	**Purpose of assessment**
EEG	Measures electrical activity within the brain. It is used to highlight areas of the brain responsible for processing specific information.	Used to identify central processing differences.
Functional brain MRI	Measures changes in blood flow within the brain which occurs with brain activity. It is used to highlight areas of the brain responsible for processing specific information.	Used to identify central processing differences.
Neurocognitive tests	Used to assess different aspects of brain function. A number of tests exist that can provide results regarding visual memory performance, visual processing performance and reaction times to visual stimuli	Used to identify local and central visual processing differences
Trail making test	Used to assess an individual's visual attention and ability to task switch.	Used to identify differences in local visual function.
Gaze tracking	Assesses the motion of the eye relative to the head or where the individual's gaze is focusing on.	Used to identify differences in local visual function.
Posturography	Used to measure an individual's postural control while upright under varying conditions (static or dynamic)	Used to identify central processing differences.
Reaction to visual stimuli	Used to measure an individual's ability to react to a visual stimuli. The task required of the individuals may vary between research papers (eg. pressing a button in response to the visual stimulus or making a postural adjustment)	Used to identify differences in local visual function.

Abbreviations: EEG= electroencephalogram and MRI= magnetic resonance imaging

Visual contribution to motor control

Nine studies (Wikstrom et al., 2017; Grooms et al., 2018; Lion et al., 2018; Friden et al., 1998; Miko et al., 2021; Chaput et al., 2021b; Bartels et al., 2019; Roelofsen et al., 2020; Clark et al., 2014) examined the contribution of vision to motor control in ACLR population as compared

to healthy controls, with six (Miko et al., 2021; Chaput et al., 2021b; Bartels et al., 2019; Grooms et al., 2018; Clark et al., 2014; Roelofsen et al., 2020) finding ACLR had increased contribution . During both postural and movement tasks, visual reliance was determined by a participants' balance and movement control worsening, respectively, with the removal or alteration of visual input. Contrastingly, four studies (Wikstrom et al., 2017; Lion et al., 2018; Grooms et al., 2018; Friden et al., 1998) reported no significant difference. This conflict may be due to large heterogeneity in testing methodologies and data analysis techniques. A systematic review with meta-analysis (Wikstrom et al., 2017) demonstrated no significant difference between ACLRs and healthy controls in their performance during a single leg postural control task which compared eyes open to eyes closed; both groups experienced similar declines in performance when their vision was blinded (ACLR= 42.9% decline versus controls= 44.4% decline). The studies included in this meta-analysis used traditional centre of pressure metrics (path, amplitude, and calculated stability indexes). However, posturography and frequency analysis during double leg standing utilised in three studies demonstrated increased reliance on the visual system (via assessment of ultra-low frequencies) in the ACLR population as compared to healthy controls (Bartels et al., 2019; Wein et al., 2021; Clark et al., 2014). This was further support by Chaput and colleagues (2021) who demonstrated higher performance on a visual motor subscale in a neurocognitive test was strongly associated with better time-to-stability performance during a jump-landing task (r= -0.61, p=0.03) in an ACLR population, whilst no such association was found in healthy controls (Chaput et al., 2021b).

Four studies (Bjornaraa and Di Fabio, 2011b; Friden et al., 1998; Wein et al., 2021; Roelofsen et al., 2020) examined within-subject differences in the ACLR vision contribution to motor control with mixed findings. Two studies (Wein et al., 2021; Roelofsen et al., 2020) demonstrated significant reductions in posturography (Wein et al., 2021) and leg positioning task (Roelofsen et al., 2020) performance whilst two studies (Friden et al., 1998; Bjornaraa and Di Fabio, 2011b) demonstrated no significant difference during a change of direction (Bjornaraa and Di Fabio,

2011b) and hopping (Friden et al., 1998) task. The two studies (Wein et al., 2021; Roelofsen et al., 2020) demonstrating significant differences compared the ACLR limb post-surgery to the limb prior to surgery, whilst the two studies (Friden et al., 1998; Bjornaraa and Di Fabio, 2011b) demonstrating no significant difference examined differences between the ACLR limb and uninjured limb, potentially indicating that individuals become more reliant on visual information following ACLR. The two studies (Friden et al., 1998; Bjornaraa and Di Fabio, 2011b) which demonstrated no significant difference utilised functional tests such as hop for distance (blinded versus full vision) (Friden et al., 1998) and a change of direction (full vision versus disrupted vision) (Bjornaraa and Di Fabio, 2011b) whilst the two studies (Roelofsen et al., 2020; Wein et al., 2021) demonstrating a difference utilised tests requiring small adjustments in posture. This may suggest that whole-body functional tasks could allow for compensatory movements from other body segments which mask the altered motor control within the ACLR limb.

1 Table 2.12.4.F. Studies examining changes to the visual system following ACLR

Level of visual system	Authors	Participant information	Time from surgery (months)	Outcome measure used	Task	Results
Central visual processing						
Significant reduction in function (p<0.05)	(Chaput et al., 2021a) Comparative study	ACLR (n= 16, 37.5% male) 21.5 ± 2.6 yrs Healthy Controls (n= 15, 40% male) 22.9 ± 3.0yrs	41.4 ± 33	ImPACT and functional brain MRI	ImPACT: computer based Functional brain MRI: supine knee flexion and extension	↑ activity in visual sensory cortical area in ACLR group and significantly associated with visual memory and visual motor scores on ImPACT
	(Criss et al., 2020) Comparative study	ACLR (n= 15, 47% male) 20.9 ± 2.7 yrs Healthy Controls (n=15, 47% male) 22.5 ± 2.5yrs	43.3 ± 33.1	Functional brain MRI	Supine heel slide	Greater activation in ipsilateral superior parietal lobule lateral occipital cortex and angular gyrus as compared to controls (z-max= 5.26)
						Greater activation in ipsilateral occipital fusiform gyrus and white matter optic radiation compared to controls (z-max= 4.12)
						Greater activation in bilateral intracalcarine cortex and lingual gyrus (z-max= 6.73)
	(Grooms et al., 2017) Comparative study	ACLR (n=15, 47% male) 21.7 ± 2.7 Healthy Controls (n=15, 47% male) 23.2 ± 3.5	38.1± 27.2	Functional brain MRI	Supine knee flexion/extension	↑activation of visual-motor region (mean signal change ACLR= 0.67%, controls= 0.28%)

	(Grooms et al., 2015b) Case control case study	ACLR (n=1, 100% male) 25 yrs Healthy Control (n= 1, 100% male) 26 yrs	10	Functional brain MRI	Supine knee flexion/extension	Greater activation in contralateral lingual gyrus as compared to healthy control (peak z value= 4.50)
	(Lehmann et al., 2021a) Comparative study	ACLR (n= 12, 58% male) 25.1 ± 3.2 yrs Healthy Controls (n= 12m 58% male) 25.5 ± 3.8 yrs	1.5± 0.2	EEG	Single leg standing	↑ alpha-2 connectivity within or linking somatosensory and visual cortical areas when standing on the ACLR limb and not uninjured limb
No significant difference	(Giesche et al., 2021) Comparative study	ACLR (n=10, 100% male) 28 ± 4 yrs Healthy Controls (n=17, 100% male) 28 ± 4 yrs	63 ± 35	EEG	Jump landing	No significant difference. However, trend for greater activation in supplementary and primary motor cortex
Local visual processing						
Significant reduction in function (p<0.05)	(Armitano-Lago et al., 2020) Comparative study	ACLR (n=16, 50% male) 29.3 ± 6.9 yrs Healthy Controls (n=16, 50% male) 28.9 ± 6.2yrs	106.9 ± 71.6	Reaction time to visual stimulus	Stepping task in reaction to visual stimulus	Slower reaction time in ACLR group during simple task (ACLR= 484 ± 3.17ms, controls= 399 ± 1.95ms)
						Slower reaction time in ACLR group during choice basked reaction time task (ACLR= 550 ± 43ms, controls= 445 ± 43ms)

	(Bodkin et al., 2021) Comparative study	ACLR (n= 10, 40% male) 19.9 ± 1.7 yrs Healthy Controls (n= 10, 40% male) 21.1 ± 1.4 yrs	22.3± 15.4	Gaze tracking	Tracking moving target	↑visual gaze errors in ACLR group (ACLR= 0.52± 0.23m, controls= 0.35± 0.14m)
	(Roelofsen et al., 2020) Comparative study	ACLR (n= 14, 79% male) 23.2 ± 4.8 yrs Healthy Controls (n= 15, 67% male) 23.1 ± 3.4 yrs	4.5 to 5	Leg amplitude differentiation	Leg amplitude differentiation under various visual feedback conditions	↓Leg amplitude variability in ACLR limb as compared to healthy control limb in both visual enhanced and visual veridical conditions
						↓Leg amplitude variability in ACLR limb as compared to the limb pre-surgery in both visual enhanced and visual veridical conditions
No significant difference	(Bodkin et al., 2021) Comparative study	ACLR (n= 10, 40% male) 19.9 ± 1.7 yrs Healthy Controls (n= 10, 40% male) 21.1 ± 1.4 yrs	22.3± 15.4	Gaze tracking	Tracking stationary target	No difference in visual gaze score or visual gaze velocity between groups
	(Chaput et al., 2021a) Comparative study	ACLR (n= 16, 37.5% male) 21.5 ± 2.6 yrs Healthy Controls (n= 15, 40% male) 22.9 ± 3.0yrs	41.4 ± 33	ImPACT	ImPACT: computer based	No difference in visual motor composite score and visual memory composite score between groups

	(Stone et al., 2018) Comparative study	ACLR (n= 20, 40% male) 22 ± 3 yrs Healthy Controls (n= 20, 40% male) 22 ± 3 yrs	unclear	CogState neurocognitive test and	Reaction time to visual stimulus.	No difference in reaction time
				Purdue pegboard test	Manual dexterity and bimanual coordination	No difference in Purdue pegboard performance
Significant increase in function (p<0.05)	(Stone et al., 2018) Comparative study	ACLR (n= 20, 40% male) 22 ± 3 yrs Healthy Controls (n= 20, 40% male) 22 ± 3 yrs	unclear	Trail making test	Visual attention and task switching	ACLR group completed Trail A faster than healthy controls ($F_{(1,37)}$=5.61)
						ACLR group completed Trail B faster than healthy controls ($F_{(1,37)}$=6.27)
Visual contribution to motor control						
Significant reduction in function (p<0.05)	(Bartels et al., 2019) Longitudinal cohort study	ACLR (n=30, 47% male) 32 ± 12.2 yrs	24	Posturography	Double leg standing	↑activity in visual systems to maintain stability (η_p^2= 0.179)

	(Chaput et al., 2021a) Comparative study	ACLR (n= 16, 37.5% male) 21.5 ± 2.6 yrs Healthy Controls (n= 15, 40% male) 22.9 ± 3.0yrs	41.4 ± 33	ImPACT and time to stability test	ImPACT: computer based Time to stability following single leg landing task	Higher performance on visual motor composite score strongly associated with better time to stability performance in ACLR group ((r= -0.61, p=0.03) No association in control group
				ImPACT and joint position sense test	ImPACT: computer based Joint position sense in isokinetic dynamometer	Higher performance on visual memory composite score was strongly associated with lower JPS error (r= -0.63). No association in controls
	(Clark et al., 2014) Comparative study	ACLR (n= 45, 67% male) 26 ± 9.8 yrs Healthy Control (n= 45, 67% male) 26.4± 9.8 yrs	10.7 ± 4.3	Frequency analysis	Single leg standing	↑ value on visual system frequency (ACLR= 0.04± 0.01 cm/s, Controls= 0.03± 0.01cm/s,
	(Grooms et al., 2018) Comparative study	ACLR (n= 15, 47% male) 21.4 ± 2.6 yrs Healthy Controls (n= 15, 47% male) 23.2 ± 3.5 yrs	36.2 ± 26.5	Stroboscopic vision	Drop jump with vision obscured	↑knee flexion excursion with stroboscopic vision (ACLR= 3.1 ± 3.8°, controls= -0.8 ± 4.5°)
	(Miko et al., 2021) Cohort study	ACLR (n=14, 33% male) 20.7 ± 1.9 yrs Healthy Controls (n=14, 33% male) 21.2 ± 1.4 yrs	46.6 ± 28.1	Single leg balance	Single leg balance with dual-cognitive task	↓ postural control in ACLR group with greater ellipse area (Cohen's d= 0.44) and Root mean square in medial to lateral plane (Cohen's d= 0.49)

	(Roelofsen et al., 2020) Comparative study	ACLR (n= 14, 79% male) 23.2 ± 4.8 yrs Healthy Controls (n= 15, 67% male) 23.1 ± 3.4 yrs	4.5 to 5	Leg amplitude differentiation and temporal variability	Leg amplitude differentiation under various visual feedback conditions	↑Temporal variability in the ACLR limb and uninjured limb as compared to healthy control limb in both visual enhanced and visual veridical conditions
					Temporal variability during treadmill walking	↑ Temporal variability in the ACLR limb and uninjured limb post-operatively as compared to pre-operatively in both visual enhanced and visual veridical conditions. Main effect for ACLR limb= $F_{(1, 12)}$=11.00. p=0.006, uninjured limb $F_{(1,12)}$=17.93
	(Wein et al., 2021) Cross-sectional study	ACLR (n=50, 76% male) 27 ± 6.2 yrs	At least 6 months	Posturography	Double leg standing	↓visual ratio and increased reliance on visual cues for balance post-operatively (post-op= 3.1± 2.0 vs pre-op 5.7 ± 4.1)
No significant difference	(Bjornaraa and Di Fabio, 2011a) Comparative study	ACLR (n= 17, 0% male) 26.5 ± 6.3 yrs Healthy Controls (n= 17, 0% male) 25.3 ± 6 yrs	55.2	3D motion capture with shutter glasses	Change of direction task	No difference in biomechanics variables (such as absolute displacement, peak absolute velocity, average absolute velocity and percent of cut to reach peak ground reaction force) between full vision and disrupted vision

	(Friden et al., 1998) Comparative study	ACLR (n= 20, 50% male) 26 yrs Healthy Controls (n=40, 48% male) 25 yrs	24	One leg hop	One leg hop for distance under varying visual conditions	No difference between groups in hop distance when vision from one or both eyes was obstructed
						No difference in hop distance between ACLR limb and uninjured limb when vision from one or both eyes was obstructed
	(Grooms et al., 2018) Comparative study	ACLR (n= 15, 47% male) 21.4 ± 2.6 yrs Healthy Controls (n= 15, 47% male) 23.2 ± 3.5 yrs	36.2 ± 26.5	Stroboscopic vision	Drop jump with vision obscured	No difference in knee adduction excursion, peak vertical ground reaction force, peak knee external knee flexor moment and peak external knee abductor moment
	(Lion et al., 2018) Comparative study	ACLR (n= 19, 74% male) 24.8 ± 6.4 yrs Healthy Controls (n= 21, 52% male) 24.9 ± 3.7 yrs	9.2 ± 1.6	Double leg balance	Double leg balance under varying visual conditions	No difference in postural control performance between groups
	(Wikstrom et al., 2017) Systematic review with meta-analysis	ACLR (n=120-133) Healthy Controls (n= 162-188) Age and % male of participants unclear	unclear	Single leg balance	Single leg balance eyes open versus eyes closed	Similar decline in performance between ACLR and controls when eyes are closed (ACLR= 42.9% decline and controls= 44.7% decline). Hedges g effect size= -0.61

ACLR= anterior cruciate ligament reconstruction, MRI= magnetic resonance imaging, EEG= electroencephalogram, BPTB= bone patellar tendon bone, HS= hamstring

2

2.12.5 Discussion

The review's aim was to summarise any differences in somatosensory and visual systems following ACLR. The results identified both within-subject and between-group differences in central processing (somatosensory and visual systems) in the ACLR cohort which may represent sensorimotor dysfunction. However, when assessing somatosensory functions (such as JPS and TTDPM) and the visual system (processing central and local visual information, and the contribution of vision on motor control) there were mixed findings with a tendency for between-group (ACLR versus healthy controls) differences to be present.

Changes That Occur in the Somatosensory and Visual Systems Following ACLR

Previous reviews have focused on the negative efferent changes within the sensorimotor system following ACLR which have been hypothesised to occur in response to dysfunction within the afferent pathways (Neto et al., 2019a). It has also been hypothesised that an over reliance on the visual system to maintain postural control and execute movements may develop in response to dysfunction within the somatosensory system (Grooms et al., 2015a). The results of this review confirm that there are significant differences between the afferent pathways, both somatosensory and visual, of ACLR participants and healthy controls, and also between limbs in the ACLR cohort with studies assessing central processing demonstrating alterations in somatosensory processing and increased activity in the visual system (Criss et al., 2020; Grooms and Onate, 2015; Grooms et al., 2017). However, it is not possible to determine if the differences are a reflection of dysfunction that occurs as a result of the ACLR surgery or is present prior to surgery due to the lack of prospective research available.

As previously mentioned, the ACL is highly innervated with mechanoreceptors with damage leading to a reduction in somatosensory functions such as proprioception and kinaesthesia (Gomez-Barrena et al., 1996; Park et al., 2005). However, somatosensory functions are thought to improve once the afferent fibres regrow into the ACL graft over the following three to six months (Dhillon et al., 2012). Our review supports the notion of a reduction in proprioception (Hoshiba et

al., 2020; Relph and Herrington, 2016b; Jurevičienė et al., 2012) and kinaesthesia (Laboute et al., 2019; Courtney et al., 2019; Nagai et al., 2013) in the ACLR limb as compared to the participants' uninjured limb. Whilst some of these findings were reported for participants who were less than six months post-surgery, there was an almost equal number of studies which demonstrated persistent reduced function in participants whose ACLR graft should have been reinnervated (36 to 64 months post-surgery) (Anders et al., 2008; Büyükafşar et al., 2020; Fremerey et al., 2000; Co et al., 1993). The persistent reduced function could indicate that some individuals do not experience reinnervation of their graft (Young et al., 2016). Another more likely explanation is that these participants have ongoing dysfunction in central processing of the somatosensory information, as evidenced by the functional brain MRI and EEG studies (Baumeister et al., 2008; Valeriani et al., 1999; Bartels et al., 2019; Grooms et al., 2017; An et al., 2019), despite having received rehabilitation.

Motor control requires the afferent systems to continuously obtain information regarding the body and its position within the environment so that appropriate motor responses can be made to account for any perturbations (Savelsbergh et al., 1999; Gibson, 1986; Møller, 2003). Dysfunction within the somatosensory system may result in greater reliance being placed on the other afferent systems such as the visual system to obtain information from the environment. This has been previously shown in injuries, such as chronic ankle instability (Song et al., 2016). The results of our review appear to support the notion that increased reliance on the visual system also occurs in the ACLR cohort. Four studies utilising methods to assess central processing in the visual centres demonstrated greater activity in these centres as compared to healthy controls during simple motor tasks (Chaput et al., 2021a; Criss et al., 2020; Lehmann et al., 2021a; Grooms et al., 2017; Grooms et al., 2015b). It has previously been suggested that increased reliance on the visual system may increase the risk of sustaining a primary ACL injury, potentially as a result of the athlete either missing environmental cues or reacting slowly to a stimulus, thereby executing a movement with poorer technique (Swanik et al., 2007). Therefore, increased reliance on the

visual system identified in individuals following ACLR may have an implication for increased risk of second ACL injury (Grooms et al., 2015b). Bodkin and colleagues (2021) reported that ACLR participants exhibited significantly greater visual gaze errors as compared to healthy controls when tracking a moving target. The findings may provide some support for the notion of ACLRs being more visually reliant as they found it harder to track a moving target, although it may also represent that this population has poorer visual function, which is pertinent for picking up cues in a chaotic environment which is encountered is most field-based sports. The findings were supported by Armitano-Lago and colleagues (2020) who reported that ACLR participants responded slower to a visual stimulus than healthy controls when tasked with making a postural adjustment. Slower reaction times were seen in the ACLR group when performing a stepping task but not so when completing a task whilst seated, suggesting that as task complexity increases, then individuals with dysfunction within motor planning and execution cortical areas will begin to demonstrate differences.

A Reflection on Assessing Somatosensory and Visual Dysfunction

Although differences have been found to exist in the somatosensory and visual systems following ACLR, a common issue for clinicians is having the tools to identify this dysfunction in their athletes. Central processing changes are identifiable via methods such as functional brain MRI and EEG. However, both methods are not feasible for many clinicians due to the cost and lack of access to the technology. An alternative approach to identifying somatosensory dysfunction may be possible by identifying JPS or TTDPM deficits in athletes greater than six months post-surgery. The most appropriate method to measure JPS would be image-calculated angulation because most clinicians do not have access to isokinetic dynamometers. However, very few studies have published the reliability of the outcome measures they used which can make it difficult for clinicians to utilise in clinical practice. One study (Relph and Herrington, 2016b) which utilised image-calculated angulation to measure JPS published the reliability (ICC= 0.86-0.92) and minimal detectable change (1.3° to 2.4°) for their testing methodology (Relph and Herrington,

2015b), therefore allowing it to easily be employed in clinical practice. With regards to TTDPM, there are a limited number of methods to assess TTDPM without using isokinetic dynamometers. Hence, more research is required to find reliable methods to assess TTDPM that are also easy for clinicians to employ within their clinics. So, the reality for clinicians is that deficits likely occur in some, if not all, individuals following ACLR. However, they are unlikely to be able to assess these deficits in the clinic, so clinicians should employ exercises which redevelop these qualities.

With regards to assessing the visual system, there was again large heterogeneity in the outcome measures used. This is especially evident in the variety of outcome measures used to assess local visual processing function (e.g. trail making test, gaze tracking and neurocognitive testing). Whilst there may be differences identified in gaze tracking (Bodkin et al., 2021) or trail making tests (Stone et al., 2018), it is still not clear what impact this has on the ACLR cohort with regards to risk of reinjury or sporting performance. More prospective research is needed to identify the attributes of visual processing that are most pertinent for athletes following ACLR to minimise the risk of reinjury and to return to preinjury performance levels. Previous research has identified visual memory, processing speed and reaction times on a neurocognitive test as factors associated with greater risk sustaining a primary ACL injury (Swanik et al., 2007). The greater availability of sensory stations (Burris et al., 2020) (mobile tablet technologies with preloaded visual assessments) which assess these factors plus a number of other local visual processing attributes may make it easier for not only clinicians to assess athletes with a single tool but also for researchers to have a consistent outcome measure to measure athletes for prospective studies. When assessing the effect of vision on movement control, posturography with analysis of frequencies currently appears to be a consistent method to identify if there is an over-reliance on the visual system during static tasks (Wein et al., 2021; Clark et al., 2014) but it may not be feasible for clinicians as there are only a few commercially available systems. In summary, visual reliance most likely exists along with some dysfunction of visual processing in the ACLR population

but methods of measurement are limited for clinicians. Clinicians should look to include training modalities that improve visual processing.

Clinical Implications for Rehabilitation

Current ACLR rehabilitation programs follow a common path of: (1) regaining range of motion and control of the knee, (2) strength and hypertrophy training, (3) plyometric training, (4) running (linear and multi-directional) and (5) sports-specific drills (Adams et al., 2012; Lobb et al., 2012; van Melick et al., 2016). Alongside the structured rehabilitation program, athletes go through a process of gradual reintroduction to training in the sport itself prior to a reintroduction to competition. However, much of the literature which identified dysfunction within the central processing of somatosensory (An et al., 2019; Baumeister et al., 2008; Grooms et al., 2017) and visual information (Grooms et al., 2017; Criss et al., 2020) was conducted in patients who had already completed rehabilitation (although the specific makeup of their rehabilitation programs was not reported) and returned to sport (average time from surgery ranged between 12 and 48 months). If the participants had completed rehabilitation that would be expected as standard care, then this continued dysfunction could suggest that there is a missing element in either current rehabilitation programs or the long-term follow up care of athletes. Hence, future research is required to identify (1) methods applicable to a clinical setting to identify individuals with a deficit and then (2) methods to reduce the reliance on the visual system.

Along with identifying methods to reduce visual reliance, knowing when to implement these methods is important as well. Proprioception deficits have been identified within the first four weeks following ACLR (Laboute et al., 2019), and Lehmann and colleagues (2021) have also demonstrated that increased reliance on the visual system (at the central processing level) may begin within six weeks following ACLR. The results suggest that clinicians aiming to reduce reliance on the visual system need to implement interventions very soon post-operatively. Therefore, future research should aim to identify effective methods to reduce reliance on the visual system.

Limitations

There are several limitations to our scoping review. Firstly, much of the research identified was retrospective in nature meaning that it is not possible to determine if any of the identified somatosensory and visual dysfunction in the ACLR cohort was present prior to the injury or prior to the ACLR. Secondly, no critical appraisal of the studies was performed due to the small number of studies in area of somatosensory and visual dysfunction, so threats of bias were not identified within the selected studies, and this may affect the results obtained. However, because visual dysfunction is quite a new area of research in the ACLR literature, the decision was made to include all available studies so that trends could be observed. As this area of science matures, then future studies could be more selective in the quality of studies that they use for review. Furthermore, the review predominantly examines somatosensory and visual variables but not how it relates to patient outcomes. Future research should assess how these variables are associated to patient outcomes. Another limitation was that there were several studies utilising participants who were greater than two years post-ACLR. This may potentially introduce confounders to the results as the participants had been discharged from rehabilitation and returned to general activity. Therefore, it is unknown what influence returning to general activity may have on afferent function. Lastly, the reliability of a number of the outcome measures used in the selected studies were not reported, making it difficult to confidently trust the statistical and clinical significance of the differences observed.

2.12.6 Conclusion

This scoping review highlights the within-subject (ACLR limb vs uninjured limb) and between-group (ACLR versus healthy controls) differences within the somatosensory and visual. The evidence highlighting differences in central processing of the somatosensory and visual systems demonstrates the potential impact that ACL injury and/or ACLR has on individuals. Within the somatosensory system, reduced proprioceptive and kinaesthetic function has been demonstrated in the ACLR limb as compared to the contralateral uninjured limb. Similarly, the

ACLR limb has reduced proprioceptive and kinaesthetic function as compared to healthy controls. Increased reliance on the visual system occurs in response to somatosensory dysfunction as evidenced by altered central processing, potentially resulting in errors in visual processing and adversely affecting motor control.

Future large studies are required to examine if there are differences in visual processing between athletes following ACLR and healthy controls. Similarly, more research is required to examine the effect of visual reliance on biomechanics and also the effectiveness of interventions in treating these dysfunctions as well.

Relevance of scoping review findings on the thesis:

The findings of the scoping review demonstrated that there were clear alterations in the cortical visual processing centres during simple motor tasks following ACLR. This reinforces the theory that a reweighting occurs following ACLR due to altered somatosensory function. Although there were mixed findings regarding proprioceptive and kinaesthetic function, it was generally seen that proprioceptive and kinaesthetic differences were small but statistically significant in the early months of rehabilitation and less significant after approximately six months from the ACLR. However, it would suggest that if assessing individuals for visual reliance, then a proprioceptive or kinaesthetic assessment should also be conducted to determine if it is a confounding factor. Therefore, for the investigative study (Chapter 4) aiming to identify visual reliance in an ACLR cohort, a joint position sense test was included. The scoping review also highlighted the large heterogeneity in visual processing assessment tools and the lack of studies with large participant numbers. Therefore, Chapter 5 and 6 aim to determine the reliability of a tablet system which assesses visual processing ability and to implement this system within a large cohort of ACLR and healthy controls to determine if any difference exist.

2.13 The biomechanical risk factors of ACLR reinjury

All injuries occur when the load placed on the structure exceeds its load bearing capacity either via cumulative overload or a single event of overload (Bertelsen et al., 2017). Hence, ACLR reinjuries occur when the rate and/or magnitude of loading on the ACL graft is greater than its capacity. Both the rate and magnitude of load are influenced by an athlete's movement technique. Therefore, examination of the biomechanics of an athlete's movement technique is essential to understand the potential factors that may place excessive loads on the ACL graft, thereby allowing clinicians to positively affect change on these variables to reduce the likelihood of reinjury. To conceptualise potential risk factors for ACLR reinjury, it is important to understand the factors that result in primary ACL injury and also the changes that occur to these factors following an ACLR that may then result in ACLR reinjury.

It is commonly accepted that prospective cohort studies are hierarchically superior to retrospective studies in determining risk factors for injury (McNair and Lewis, 2012). However, there is a current lack of prospective and retrospective studies investigating biomechanical risk factors for ACLR reinjury. Therefore, studies investigating biomechanical risk factors and associated factors for primary ACL injury may be utilised to identify potential risk factors for ACLR reinjury.

2.13.1 External knee valgus moment

External knee valgus moment has been demonstrated to increase the strain on the ACL when in combination with other forces such as quadriceps force and compression during in vitro and simulation studies (Withrow et al., 2006; Quatman and Hewett, 2009). No prospective research has been completed to identify a relationship between external knee valgus moments and ACLR reinjury. Therefore, research surrounding primary ACL injury is required to examine whether external knee valgus moments have a relationship with ACL injury. Four prospective studies, utilising drop jump testing (Hewett et al., 2005; Krosshaug et al., 2016; Leppänen et al., 2016) and a 90° CoD task (Pasanen et al., 2025), examined the relationship between external knee

valgus moment and primary ACL injury. Hewett and colleagues (2005) demonstrated that in their cohort of adolescent females that those who sustained a primary ACL injury exhibited significant greater external knee valgus moment during a landing task as compared to those who did not injure their ACL (Injured: 0.74 ± 0.46Nm/kg, Uninjured: 0.31 ± 0.26Nm/kg, P<0.001). However, these findings are in stark contrast to the those of Leppänen and colleagues (2016), Krosshaug and colleagues (2016) and Pasanen and colleagues (2025) which found no significant difference in external knee valgus moments in those who sustained a primary ACL injury and those who did not. The conflicting results are presented in table 2.13.1.A. Three retrospective studies (Stearns and Pollard, 2013; Lee et al., 2014; King et al., 2019) examined external knee valgus moments during CoD tasks (Stearns and Pollard, 2013) and jumping tasks (King et al., 2019) following ACLR (see table 2.13.1.B.). There were contrasting findings between the three studies. Stearns and Pollard (2013) demonstrated that a group of 12 female soccer players following ACLR exhibited significantly greater external peak knee valgus moment (ACLR: 1.33 ± 0.5, controls: 0.80 ± 0.4Nm/kg, p=0.004) during the first 20% of stance phase as compared to controls. This was contrasted by King and colleagues (2019) which demonstrated reduced external knee valgus moment in the ACLR limb during a double leg drop jump and a single leg hop for distance, and Lee and colleagues (2014) which demonstrated that a group of 11 (eight females and three males) demonstrated no significant difference in peak external knee valgus moment as compared to controls.

The conflicting evidence from these studies suggests a clear conclusion regarding external knee valgus moment and ACLR reinjury risk is difficult to elucidate. Further larger cohort prospective studies would need to be conducted to define a clear relationship.

2.13.2 Internal knee flexor moment

High knee flexor moments may be protective of ACL injury by minimising the anterior shear forces within the knee during loading tasks such as landing and walking(Palmieri-Smith et al., 2019). A systematic review with meta-analysis (Sajedi et al., 2025) demonstrated significantly reduced internal peak knee flexor moment in the ACLR limb as compared to the uninjured limb whilst walking. This significant difference was noted in cohorts less than 12 months post-surgery but was not significant in cohorts greater than 12 months post-surgery (Sajedi et al., 2025). Similarly, it was found that during a double leg landing task from a 31cm box, the ACLR limb demonstrated significantly reduced internal knee flexor moment as compared to the uninjured leg between 6 and 18 months post-surgery but not at 24 months post-surgery (Sharafoddin-Shirazi et al., 2020). No study to date has reported differences in internal knee flexor moment during a CoD task.

The results highlight that knee flexor moments are reduced following ACLR and may be associated with ACLR reinjury due to the reduced ability to utilise the hamstrings to diminish anterior shear forces within the knee.

Table 2.13.1.A. Prospective research regarding external knee valgus moment and primary ACL injury

	Author	No. of participants	Males:Females	Age (years)	Sporting background	Level of sport	Follow up period	Testing manoeuvre	No. ruptures	Peak knee valgus moment (N·m/kg)
Prospective studies for primary ACL injury	***(Hewett et al., 2005)***	**205**	**Males: 0 Females: 205**	**ACL: 15.8 ± 1.0 Uninjured: 16.1 ± 1.7**	**Soccer Basketball Volleyball**	**Unknown**	**13 months**	**30cm DL Drop Jump**	**9**	**ACL: -0.74 ± 0.46 Uninjured: -0.31 ± 0.26 (P<0.001)**
	(Krosshaug et al., 2016)	710	Males: 0 Females: 710	21±4	Soccer Handball	Elite	7 years	30cm DL Drop Jump	42	ACL: 0.33 ± 0.18 Uninjured: 0.31 ± 0.16 (p=0.47)
	(Leppänen et al., 2016)	171	Males: 0 Females: 171	15.4 ± 1.9	Basketball Floorball	Club	3 years	30cm DL Drop Jump	15	ACL: 0.61 ± 0.41 Uninjured: 0.51 ± 0.33 (p=0.32)
	(Pasanen et al., 2025)	65	Males: 0 Females:65	ACL: 18.7 ± 3.2 Uninjured: 19.6 ± 4.4	Floorball	Club	2.5 years	90° CoD	10	ACL: 1.16 ± 0.62 Uninjured: 1.19 ± 0.49 (P>0.05)

Abbreviations: ACL= anterior cruciate ligament, DL= double leg, CoD= change of direction

Table 2.13.1.B. Retrospective research regarding external knee valgus moments during change of direction tasks

	Author	No. of participants	Males:Females	Age (years)	Sporting background	Level of sport	Years since ACLR	Testing manoeuvre	Internal adductor moment (Nm/kg)
Cohort studies post-ACLR	***(Stearns and Pollard, 2013)***	**24**	**Males: 0 Females: 24**	**ACLR: 21 ± 1.9 Control: 21.3 ± 1.2**	**soccer**	**unknown**	**46.3 ± 39.7 months**	**45° CoD**	**ACLR 1.33 ± 0.5 Control: 0.80 ± 0.4**
	(Lee et al., 2014)	22	Males: 6 Females: 16	ACLR: 21 ± 2 Control: 21 ± 1	unknown	unknown	1.7 ± 1.2 years	45° CoD	ACLR: 0.49 ± 0.26 Control: 0.47 ± 0.26
	(King et al., 2019)	**218**	**Males: 218 Females: 0**	**ACLR: 24.8 ± 4.2 Control: 24.7 ± 3.9**	**Field-sport**	**Recreational**	**0.8 ± 0.1 months**	**DL drop jump**	**ACLR limb demonstrates reduced knee valgus Asymmetry ACLR= 0.78 ± 0.35 & Controls= 0.47 ± 0.35 (p<0.05)**
								Single leg hop for distance	**ACLR limb demonstrates reduced knee valgus Asymmetry ACLR= 0.80 ± 0.40 & Controls= 0.52 ± 0.40 (p<0.05)**

Abbreviations: ACLR= anterior cruciate ligament reconstruction, DL= double leg, CoD= change of direction, shading of cells= significant difference with p<0.05

2.13.3 Internal knee extensor moment

The ACL's primary role is to limit anterior tibial translation in relation to the femur (Girgis et al., 1975; Markolf et al., 1995; Markolf et al., 1976). Anterior shear forces placed on the knee which are greater than the load capacity of the ACL will lead to fibre disruption which could ultimately lead to rupturing as evidenced in *in-vitro* studies (Renström et al., 1986; Fleming et al., 2001). A significant contributor to large injurious anterior shear forces within the knee is a large internal knee extensor moment, especially in the context of a large eccentric quadriceps contraction with reduced co-activation of the hamstrings (DeMorat et al., 2004; Yu and Garrett, 2007). Large internal knee extensor moments are encountered during actions that have been shown to lead to ACL injury such as landing and CoD tasks (Shelburne et al., 2004).

Landing tasks

Whilst it is known that prospective research is the strongest form of evidence to identify risk factors for ACLR reinjury, there is currently no prospective literature investigating internal knee extensor moments and ACLR reinjury. However, there are a number of retrospective studies (Goerger et al., 2015; Decker et al., 2002; Dai et al., 2014; Ortiz et al., 2008; King et al., 2019; Lepley and Kuenze, 2018) (see table 2.13.3) which examine internal knee extensor moments during double and single leg jump-landing tasks with contrasting findings. A systematic review with meta-analysis (Lepley and Kuenze, 2018) demonstrated a significant reduction in internal knee extensor moment in the ACLR limb during double-leg landing tasks when compared to the contralateral uninjured limb (Cohen d= -1.23, 95% CI= -1.86, -0.60) and to healthy controls (combined Cohen d range= -0.92, 95% CI= -1.45, -0.38). Pooled results for single leg drop landings found similar significant reductions in internal knee extensors moments of the ACLR limb in comparison to the contralateral uninjured limb (Combined Cohen d= -0.74, 95% CI= -1.51, -0.03) but mixed findings when compared to healthy controls (combined Cohen d= -0.10, 95% CI -1.27, 1.07) (Lepley and Kuenze, 2018). The findings of reduced internal knee extensor moment are potentially due to the inadequate return of quadriceps function post-surgery (Gohil et al., 2025).

None of the studies assessed quadriceps strength so it cannot be determined if poor quadriceps function was the cause of reduced internal knee extensor moments. Another potential cause for the reduced internal knee extensor moment in the ACLR limb may be due to the participants employing an offloading strategy by either loading the contralateral uninjured limb more (during double leg landing tasks) or by utilising a technique such as increasing hip or trunk flexion (during single and/or double leg landing tasks). To determine if an offloading strategy is being employed, a higher loading task such as a single leg drop jump may be more beneficial because it minimises the ability of participants to compensate via their technique (e.g. increasing trunk or hip flexion).

A single study (Ortiz et al., 2008) examined single leg drop jumps and reported a significant increase in the internal knee extensor moment of the ACLR limb in comparison to healthy controls (Ortiz et al: ACLR= 3.5 ± 0.7Nm/kg and controls= 3.0 ± 0.6Nm/kg)(see table 2.13.3). Interestingly, there was no significant difference between the ACLR limb and the uninjured contralateral limb which suggests that the ACLR participants adopted techniques that generated larger internal knee extensor moments bilaterally as compared to healthy controls. Drop jump assessments may have better carry-over to sporting populations as it represents an action (rebounding off the ground to perform another jump or explosive manoeuvre) that is performed more often on the field than a simple landing manoeuvre (sticking a landing and remaining stationary afterwards). Further prospective research is required to determine if those completing drop jumps with large internal knee extensor moments are at risk of injuring their ACL. The findings Ortiz and colleagues (2008) contrast the double and single leg landing tasks examined in the previous paragraph which demonstrated ACLR participants landing with reduced internal knee extensor moments. Therefore, the findings highlight that single leg drop jump assessments may provide clinicians insight as to whether ACLR patients are placing increased shear forces on the ACL.

Change of direction

There are no prospective studies investigating internal knee extensor moments during change of direction tasks in the ACLR population. Only one retrospective study to date has published data on internal knee extensor moment during a change of direction task (Dai et al., 2014). A cohort of ACLR patients, on average 6.2 months post-surgery, performed a 35° cutting task and demonstrated significantly reduced internal knee extensor moment on the ACLR limb in comparison to their uninjured contralateral limb (ACLR limb= 0.13 ± 0.04 Nm/kg, contralateral limb 0.17 ± 0.03 Nm/kg). The difference could be the result of inadequate quadriceps function or increased co-activation of the hip extensors and hamstrings (Hirokawa et al., 1991), but more research is needed. Given the lack of research utilising COD tasks which are a known injury action for the ACL (Havens and Sigward, 2015) and its relationship with internal knee extensor moments, this indicates a need for further research in this area.

Table 2.13.3. The relationship between internal knee extensor moment and ACL injury during landing and CoD tasks

Author	No. of participants	Males:Females	Age (years)	Sporting background	Level of sport	Years since ACLR	Testing manoeuvre	Extensor moment (Nm/kg)	Contralateral limb extensor moment (Nm/kg)
(Trigsted et al., 2017)	64	0M 64F	ACL 18.8 ± 1.7 Uninjured 19.2 ± 1.0	Unknown tegner score 6	unknown	31.9 ± 19.4 months	SL hop for distance	ACL injured -1.5 ± 0.3 Control -1.6 ± 0.3	-1.6 ± 0.3
(Webster et al., 2012)	26	26M 0F	ACL 27.0 ± 5.9 Controls 22.6 2.6	Jumping and pivoting sports	unknown	67 ± 8.4 weeks	SL drop landing	ACL injured 1.09 ± 0.34 Control 1.06 ± 0.32	1.30 ± 0.38
(Goerger et al., 2015)	51	28M 23F	ACL 18.64 ± 0.50 Uninjured 18.48 ± 0.46	Naval academy	NA	Approx. 2 years	DL drop vertical jump	ACL injured – 0.17 ± 0.04 (N/BW*HT) Uninjured -0.20 ± 0.04 (N/BW*HT)	NA
(Decker et al., 2002)	22	unreported	ACL 27.3 Controls 26.9	Recreational jumping athletes	Recreational	>1 year	DL drop landing	ACL injured 12.77 ± 3.21 (%BW*ht) Control 17.47 4.97 (%BW*ht)	NA
(Ernst et al., 2000)	40	28M 12F	ACL 23.5 ± 3.7 Control 22.7 ± 4.2	Tegner 5.5	unknown	9.8 ± 2.3 months	SL vertical jump	ACL 1.30 ± 0.59 Control 1.91 ± 0.45	2.09 ± 0.49
(Orishimo et al., 2010)	13	9M 4F	ACL 33 ± 10	unknown	unknown	4-12 months	SL hop for distance	ACL 3.30 ± 1.70	3.59 ± 1.10
(Ortiz et al., 2008)	29	0M 29F	ACL 25.4 3.1 Control 24.6 2.6	multisport	Non-competitive	7.2 4.2 years	Repeated SL hop to a step	ACL 3.0 ± 0.60 Control 2.80 ± 0.52	NA
							SL drop vertical jump	ACL 3.50 ± 0.69 Control 3.00 ± 0.55	NA
(Dai et al., 2014)	23	9M 14F	ACL 16.5 ± 1.3	unknown	unknown	6.2 ± 0.6 months	DL stop jump	ACL limb 0.104 ± 0.032 Uninjured limb 0.142 ±0.030	0.142 ± 0.030
							35° cut	ACL limb 0.127 ± 0.043 Uninjured limb 0.168 ± 0.034	0.168 ± 0.034

Abbreviations: ACL= anterior cruciate ligament, SL= single leg, DL=double leg, CoD= change of direction, %BW*HT= percentage bodyweight x height, N/BW*HT= Newtons/(bodyweight x height), shading of cells= significant difference with $p<0.05$

2.13.4 Peak knee valgus angle

Peak knee valgus angle has only been examined in one prospective study regarding ACLR reinjury (Paterno et al., 2010). It reported that those who went on to reinjure their ACL following an ACLR had a significantly higher peak knee valgus angle during a double leg drop jump as compared to those who did not reinjure (reinjured group=16.2°, uninjured=12.1°, OR 3.5) (see Table 2.13.4.A). A further four studies were found in the literature review: two prospective paper investigating primary injury (Hewett et al., 2005; Pasanen et al., 2025) and two retrospective studies following a first time ACLR (Ortiz et al., 2008; Trigsted et al., 2017). The results from the Hewett and colleagues (2005) paper supported the findings of Paterno and colleagues (2010) with those sustaining an ACL injury exhibiting greater peak knee valgus angle during a double leg drop jump (injured=9°, uninjured=1.4°). However, these results are contrasted by the other prospective study (Pasanen et al., 2025) which demonstrated no significant difference in peak knee valgus angle during a CoD task between those who went on to sustain an ACL injury and those who did not. This was also supported by two cohort studies in ACLR participants who demonstrated no significant difference in peak knee valgus angle during single leg landing tasks between ACLRs and controls (Ortiz et al., 2008; Trigsted et al., 2017) (see Table 2.13.4.B). Ortiz and colleagues (2008) found no significant difference in peak valgus angle between those post-ACLR and healthy controls during a single leg 40cm drop jump and also a single leg repeated hopping tasks to a 20cm step. Trigsted and colleagues (2017) also found no significant difference in peak knee valgus angle during a single leg horizontal hop for distance between those post-ACLR and healthy controls (ACLR: 4.8 ± 7.6, Control: 4.7 ± 11.3, $p>0.05$). The contrasting results studies may be due to the ages of cohorts. The participants in the two prospective studies demonstrating a significant difference in peak valgus angle had an average age of 15-16 years, whilst the average ages of the other studies were greater than 18 years. This could suggest that whilst peak knee valgus angle is a risk factor for ACLR reinjury and primary injury, it may be a more important variable to be measured in adolescents. Further prospective research would need to be

conducted in adults to determine if increased peak knee valgus angle is a risk factor for ACLR reinjury.

2.13.5 Knee valgus angle at initial contact

As discussed in the previous section (section 2.13.4), increased peak knee valgus angle is potentially a risk factor for ACL injury which may relate to the high load being placed on the ACL in the abducted position (Quatman and Hewett, 2009; Kacprzak et al., 2024). There are no prospective or retrospective studies assessing the relationship between ACLR reinjury and knee valgus angle at initial contact. However, four prospective studies for injury (Hewett et al., 2005; Krosshaug et al., 2016; Leppänen et al., 2016; Pasanen et al., 2025) and a retrospective study (Stearns and Pollard, 2013) examined knee valgus angle at initial contact and its relationship to primary ACL injury with conflicting results (tables 2.13.5.A and 2.13.5.B). Three of the four prospective studies (Hewett et al., 2005; Krosshaug et al., 2016; Leppänen et al., 2016) examined knee valgus angle at initial contact during a double leg drop jump with contrasting results whilst the fourth study utilised a CoD task and demonstrated no significant difference between those who sustained an ACL injury and those who did not (Pasanen et al., 2025). Hewett and colleagues (2005) reported a significant increase in knee valgus angle in those who subsequently suffered an ACL injury (injured=5°, uninjured= -3.4°). However, both Leppännen and colleagues (2016) and Krosshaug and colleagues (2016) both showed no significant difference between groups. Stearns and Pollard (2013) utilised a 45° cutting task to compare frontal knee ROM differences between those who had undergone an ACLR and healthy controls. They showed that those who had undergone an ACLR demonstrated significantly greater knee valgus angle at initial contact (ACLR=3.8°, healthy=1.8°). Overall, there is contrasting evidence that increased knee valgus angle at initial contact during a drop jump and CoD is a risk factor for ACL injury, thereby necessitating further prospective research.

Table 2.13.4.A. The relationship between peak knee valgus angle and ACL injury during landing and CoD tasks

Author	No. of participants	Males:Females	Age (years)	Sporting background	Level of sport	Follow up period (years)	Testing manoeuvre	No. ruptures	Peak knee valgus angle (°)	Odds ratio (CI)
Prospective study for ACLR reinjury										
(Paterno et al., 2010)	56	Males:21 Females: 35	ACL: 15.77 ± 1.36 Uninjured: 16.60 ± 3.29	Various sports	unknown	1	31cm DL Drop jump	13	Injured: 16.2 Uninjured 12.1	3.5 (1.3-9.9)
Prospective studies for primary ACL injury										
(Hewett et al., 2005)	205	Males: 0 Females: 205	ACL: 15.8 ± 1 Uninjured: 16.1±1.7	Soccer Basketball Volleyball	Unknown	1.1	31cm DL Drop jump	9	Injured: 9 Uninjured: 1.4 (P<0.01)	Not reported
(Pasanen et al., 2025)	65	Males: 0 Females:65	ACL: 18.7 ± 3.2 Uninjured: 19.6 ± 4.4	Floorball	Recreational	2.5	90° CoD	10	ACL: 12.7 ± 10 Uninjured: 12.1 ± 10.3 (p>0.05)	1.0 (0.93-1.06)

Abbreviations: ACL= anterior cruciate ligament, DL= double leg, CoD= change of direction, shading of cells= significant difference with $p<0.05$

Table 2.13.4.B. Cohort study examining retrospective relationship between peak valgus angle and ACLR

Author	No. of participants	Males:Females	Ages (years)	Time since ACLR (years)	Sporting background	Level of sport	Testing task	Peak knee valgus angle (°)
Ortiz (2008)	29	Males :0 Females: 29	ACLR: 25.4 ± 3.1 Control: 24.6 ± 2.6	7.2 ± 4.2	Fitness activities (jogging, running, weight lifting)	Recreational	SL 40cm drop jump	ACLR: 7.15 ± 5.81 Control: 9.89 ± 5.34 (P=0.179)
							SL repeated hopping (20cm step)	ACLR: 6.09 ± 5.02 Control: 5.80 ± 3.84 (P=0.14)
(Trigsted et al., 2017)	64	Males: 0 Females: 64	ACLR: 18.8 ± 1.7 Control: 19.2 ± 1.0	2.7 ± 1.6	Varied- moderately heavy labour to pivoting sports	mixed	SL horizontal hop for distance	ACLR: 4.8 ± 7.6 Control: 4.7 ± 11.3 (not significant)

Abbreviations: ACLR= anterior cruciate ligament reconstruction, SL= single leg, CoD= change of direction, shading of cells= significant difference with $p<0.05$

Table 2.13.5.A. The relationship between knee valgus angle at initial contact and ACL injury during a drop jump

	Author	No. of participants	Males:Females	Age (years)	Sporting background	Level of sport	Follow up period (years)	Testing manoeuvre	No. ruptures	Knee valgus angle at initial contact (°)	Odds ratio (CI)
Prospective studies for primary ACL injury	*(Hewett et al., 2005)*	205	Males: 0 Females: 205	ACL: 15.8 ± 1 Uninjured: 16.1±1.7	Soccer Basketball Volleyball	Unknown	1.1	31cm DL Drop jump	9	Injured: 5 Uninjured: -3.4 (P<0.01)	Not reported
	(Krosshaug et al., 2016)	710	Males: 0 Females: 710	21 ± 4	Soccer Handball	Elite	7	30cm DL Drop jump	42	Injured: -2.2 ± 4.9 Uninjured: -1.8 ± 4.1 (P=0.51)	1.00 (0.69-1.45)
	(Leppänen et al., 2016)	171	Males: 0 Females: 171	15.4 ± 1.9	Basketball Floorball	Club	3	30cm DL Drop Jump	15	Injured:0.9 ± 5.8 Uninjured: -1.8 ± 6.7 (P=0.12)	1.79 (0.71-4.55) HR

Abbreviations: ACL= anterior cruciate ligament, DL= double leg, CI= 95% confidence interval, shading of cells= significant difference with p<0.05

Table 2.13.5.B. Cohort studies examining the relationship between knee valgus angle at initial contact during change of direction tasks

Author	Study type	No. of participants	Males:Females	Ages (years)	Time since ACLR (years)	Sporting background	Level of sport	Testing task	Knee valgus angle at initial contact (°)
(Pasanen et al., 2025)	Prospective for primary ACL	65	Males: 0 Females:65	ACL: 18.7 ± 3.2 Uninjured: 19.6 ± 4.4	Floorball	Floorball	Recreational	90° CoD	ACL: 7.3 ± 7.4 Uninjured: 6.2 ± 7.3
(Stearns and Pollard, 2013)	Retrospective. Participants have had ACLR	24	Males: 0 Females: 24	ACLR: 21 ± 1.9 Control: 21.3 ± 1.2	3.9 ± 3.3	soccer	unknown	45° change of direction	ACLR: 3.80 ± 2.80 Control: 1.8 ± 2.30 (P=0.03)

Abbreviations: ACL= anterior cruciate ligament, SL= single leg, CoD= change of direction, shading of cells= significant difference with p<0.05

2.13.6 Anterior shear force

The primary role of the ACL is to resist anterior translation of the tibia in relation to the femur through all angles of knee flexion, in particular between 0-30° of flexion (Takai et al., 1993; Butler et al., 1980; Ball et al., 2020). Measuring of the anterior shear force can be either direct (measuring ACL tissue strain with axial or anterior shear loading) or indirect. Whilst direct methods of assessment involve laboratory methods of applying axial or anterior shear forces on cadaveric ACLs and determining the resultant ACL strain, indirect methods involve computational modelling to determine the magnitude of anterior shear force within the knee during movements (Beaulieu et al., 2023). Another measure commonly utilised to estimate the magnitude of anterior shear force is the anterior knee force. The anterior knee force quantifies the amount of force acting of the tibia to translate it anteriorly. It has previously been shown that a large peak posterior GRF and large knee extensor and flexor moments result in increased anterior shear force during a vertical jumping task (Sell et al., 2007). Knee valgus has also been demonstrated to increase the anterior shear force on the ACL during jumping tasks (Ueno et al., 2021; Beaulieu et al., 2023). It was shown that higher peak vertical and medial GRF, reduced gluteus medius force and increased lateral pelvic tilt and hip adduction contributed to high anterior shear forces on the ACL during landing tasks (Ueno et al., 2021). Therefore, assessment of biomechanical variables during CoD that place excessive anterior shear force within the knee are required (e.g. shallow knee flexion angle at initial contact, increased knee valgus angle, increased knee valgus moment, and increased extensor moment).

2.13.7 Trunk and Pelvis

Poor control of the trunk has been observed during ACL injury events (Boden et al., 2000). This is supported with mechanistic research which demonstrated that trunk and pelvic motion can affect knee joint forces during CoD (Jones et al., 2015; Frank et al., 2013) and landing tasks (Song et al., 2023). Research in healthy controls has demonstrated that during a CoD task, side flexion of

the trunk in the opposite direction to travel (Dempsey et al., 2007) and trunk rotation towards the direction of travel (Frank et al., 2013) can lead to increased knee valgus moments. Similarly, anterior pelvic tilt may lead to poorer control of hip adduction due to reduced activation of the hip abductors (Kim et al., 2017a), and may thereby increase loading on the ACL due to increased knee valgus.

A study utilising a planned 90° CoD task within a cohort of 16 soccer players demonstrated that those who prospectively sustained a primary ACL (4 participants) injury exhibited greater trunk side flexion away from the direction of travel (ACL= -5.7° ± 11.7° and control= 4.2° ± 7.4°, $p<0.001$, Cohens d= 1.11) and contralateral pelvic drop (ACL= -12.9° ± 9.1° and control= -9.9° ± 7.7°, $p=0.022$, Cohens d=0.38) (Di Paolo et al., 2023). This was supported by King and colleagues (2021) when prospectively following ACLR patients. 31 ACLR reinjuries were recorded within two years of their surgery and they were compared to 57 ACLR patients who did not reinjure. It was shown that during an unplanned 90° CoD, those who sustained an ACLR reinjury exhibited greater asymmetry in anterior pelvic tilt (reinjury group= -4.9° ± 8.8° and no-reinjury group= 0.3° ± 5.6°, $p<0.001$, Cohens d= 0.69) and trunk side flexion away from the direction of travel (reinjury group= -4.9° ± 10.4° and no-reinjury group= 1.7° ± 8.7°, $p=0.029$, Cohens d= 0.68). Therefore, pelvic position and trunk motion are important variables to examine in CoD when assessing for ACLR reinjury risk.

2.13.8 COM to foot and knee

Foot placement in relation to the body's COM during a CoD task has been identified as a factor that could place excessive loads on the ACL (Dos'Santos et al., 2021). This was identified utilising video-based assessment of football and rugby based non-contact ACL injuries (Della Villa et al., 2020; Della Villa et al., 2021). It has been demonstrated that a larger foot placement from the COM results in higher mean knee flexion and extension moments (Dempsey et al., 2007) and

peak knee valgus moments (Jones et al., 2015) during CoD in a healthy control population, which places higher loads on the ACL and may therefore increase the risk of injury.

Only a single study has investigated COM distance between the ankle and the knee, and the risk of ACL injury. King and colleagues (2021) prospectively followed 1045 ACLR patients. 31 reinjuries were recorded within two years since their surgery and was compared to 57 ACLR patients who did not reinjure. It demonstrated that patients who reinjured had greater distance of the COM to the knee (reinjury group= 20.1 ± 42.8mm, no-reinjury group= -6.9 ± 33.3mm, p=0.21, Cohens d= 0.69) and ankle (reinjury group= 38.8 ± 57.4mm, no-reinjury group= 5.0 ± 49.9mm, p=0.43, Cohens d= 0.62) as compared to those who did not reinjure. Therefore, the distance from the body's COM to the ankle and knee are important variables to examine in CoD when assessing for ACLR reinjury risk.

2.13.9 Knee flexion angle

ACL injuries commonly occur when the knee is at near full extension as evidenced with video analysis of injuries (Olsen et al., 2004). The ACL is the primary restraint to anterior translation of the tibia between 0-30° of knee flexion and therefore can be vulnerable to large anterior shear forces (Beaulieu et al., 2023). Computer modelling of 40 males and females completing a jumping task demonstrated that a smaller knee flexion angle was related to loads that would injure ACL (male injured= 22.06° ± 8.27°, male uninjured= 36.82° ± 9.56°, p= 0.001. Females injured= 24.88° ± 5.61°, female uninjured= 32.88° ± 8.20°, p= 0.011).

Six studies have examined knee flexion angles and their relationship to ACL injury (see table 2.13.9)(King et al., 2021a; King et al., 2019; Aziminia and Abbasi, 2022; Webster et al., 2021; Di Paolo et al., 2023; Mausehund and Krosshaug, 2024). They all had similar findings with reduced flexion of the knee during loading except for a single study (Mausehund and Krosshaug, 2024) which demonstrated no difference between ACLR and control group knee flexion. The finding of

reduced knee flexion was noted on both vertical landing tasks (Webster et al., 2021) and CoD tasks (King et al., 2019). Two studies examined prospectively the effect of knee flexion angle on the risk of an ACLR reinjury. King and colleagues (2021) demonstrated that ACLR participants who sustained a subsequent ACLR reinjury had reduced knee flexion through 9-22% of stance phase during a double leg drop jump. Similarly, Mausehund and Krosshaug (2024) demonstrated that reduced knee flexion at initial contact and reduced peak knee flexion during a CoD task resulted in higher risk of ACLR reinjury. Therefore, examination of knee flexion angle during landing or CoD is important to understand the loading strategy that the athlete is employing and their risk of ACLR reinjury.

Table 2.13.9. Studies examining knee flexion angle and ACL injuries

Author		No. of participants	Males:Females	Ages (years)	Time since ACLR (years)	Sporting background	Level of sport	Testing task	Knee flexion (deg)
King (2019)	Cohort study in individuals 9 months post-ACLR	156 ACLR 62 Controls	Males: 156 Females: 0	ACLR: 24.8 ± 4.2 Control: 24.7 ± 3.9	0.8 ± 0.1	Field-sport	Recreational	Single leg drop jump	ACLR limb demonstrates reduced knee flexion Asymmetry ACLR= 6.8 ± 0.9 & Controls= 3.6 ± 1.1 (p<0.05)
								Unplanned 90° CoD	ACLR limb demonstrates reduced knee flexion Asymmetry ACLR= 9.1 ± 2.3 & Controls= 5.6 ± 4.0 (p<0.05)
King (2021)	Prospective study for ACLR reinjury	88 ACLR	Males: 88 Females: 0	Reinjury group: 21.7 ± 4.9 No-reinjury group: 22.9 ± 4.1	0.8 ± 0.3	Field-sport	Recreational	Double leg drop	Reinjury group has increased knee flexion Reinjury group: 52.7 ± 9.7 Non- reinjury group: 47.2 ± 7.1 (p=0.03)
Aziminia and Abbasi (2022)	Cohort study between ACLR and controls	17 ACLR 17 control	Males: 34 Females: 0	unreported	unreported	Field-sport	Recreational	45° CoD	ACLR limb had reduced knee flexion Asymmetry ACLR: 7.8 ± 37.5 Control: 6.8 ± 46.8 (p=0.008)
Di Paolo et al (2023)	Prospective cohort study for primary ACL injury	16 (4 ACL injured and 12 controls)	Males: 0 Females: 16	ACL: 18.3 ± 0.5 Control: 22.4 ± 4.5	N/A	Field-sport	Elite	90° CoD	ACL limb demonstrated reduced knee flexion ACL: 55.7 ± 10.5 Control: 61.3 ± 10.7 (p=0.026)

Mausehund and Krosshaug (2024)	Cohort study between controls and those with ACLR	756 (67 ACLR and 679 controls)	Males: 0 Females:756	ACLR: 23.2 ± 4.1 Control: 20.6±3.9	1.8 ± 1.7	Field and court sport	Elite	50-80° CoD	No difference knee flexion at initial contact ACLR: 25.1 ± 8.3 Control: 25.3 ± 8.9 No difference peak knee flexion ACLR: 62.4 ± 7.1 Control: 63.7 ± 6.5
Webster et al (2021)	Cohort study of ACLR	14	Males: 11 Females: 3	26 ± 6	3.3 ± 0.5	Field-sport	recreational	Single leg forward hop	No difference between ACLR limb and contralateral limb at initial contact ACLR: 17.2 ± 4.9 Contralateral: 17.2 ± 4.0
								Single leg forward hop	ACLR limb reduced peak knee flexion compared to contralateral limb ACLR: 46.8 ± 7.3 Contralateral: 52.9 ± 6.5 (p=0.003)

Abbreviations: ACLR= anterior cruciate ligament reconstruction, DL= double leg, CoD= change of direction, shading of cells= significant difference with $p<0.05$

2.13.10 Ground Reaction Forces

Ground reaction forces can influence the loading placed on the ACL (Ogasawara et al., 2024). Large vertical and posterior GRF during CoD and landing tasks have been demonstrated to increase the loading on the ACL (Weinhandl and O'Connor, 2017; Cacolice et al., 2020). It has also been shown that vertical and lateral GRFs, hip internal rotation and knee valgus angle explain 63% of the variance in knee valgus moment during 45° CoD and thereby the loading on the ACL (Sigward et al., 2015). When examining vertical GRF and its influence on ACL injury, three studies have been published (Leppänen et al., 2017; Leppänen et al., 2016; King et al., 2019) demonstrating consistent findings with CoD (reduced vertical GRF) and mixed results with jumping tasks. When examining CoD performance, Leppanen and colleagues (2017) prospectively followed a cohort of elite basketballers and volleyballers and demonstrated that those who went on to sustain a primary ACL injury exhibited lower peak vertical GRF during a 180° CoD task as compared to those who did not. Similarly, following an ACLR, King and colleagues (2019) demonstrated that ACLR participants who are nine months post-surgery demonstrated reduced vertical GRF during an unplanned 90° CoD task as compared to healthy controls. When examining a jumping task, there were mixed results (Leppänen et al., 2016; King et al., 2019). Leppanen and colleagues (2016) demonstrated that those participants who prospectively sustained a primary ACL injury demonstrated greater vertical GRF through the limb as compared to the uninjured limbs during a double leg drop jump. However, King and colleagues (2019) demonstrated ACLR participants nine months post-surgery had reduced peak vertical GRF in the ACLR limb during a single leg drop jump as compared to healthy controls.

With regards to medial GRF, only one study has examined this during a CoD task in ACLR participants nine months post-surgery (King et al., 2019). It demonstrated that ACLR participants had lower peak medial GRF during both planned and unplanned 90° CoD task as compared to healthy controls. In the same study, during a double leg drop jump, it similarly demonstrated that ACL limb had reduced peak medial GRF as compared to healthy controls.

With regards to posterior GRF, only one study has examined this during a CoD task in ACLR participants nine months post-surgery (King et al., 2019). It demonstrated that ACLR participants had lower peak posterior GRF during a planned 90° CoD task as compared to healthy controls. Similarly, during a single leg drop jump, it was shown that the ACL limb had reduced peak posterior GRF as compared to healthy controls.

Overall, the results (see Table 2.13.10) demonstrate that during CoD, reduced vertical peak GRF may be a risk factor for primary ACL injury and continues to be diminished following ACLR. Similarly, following ACLR, there is reduced medial and posterior GRF during CoD.

Table 2.13.10. Studies examining GRFs in ACL or ACLR population

Author		No. of participants	Males:Females	Ages (years)	Time since ACLR (years)	Sporting background	Level of sport	Testing task	GRF (N/kg)
Vertical GRF									
(Leppänen et al., 2017)	Prospective ACL injury study- vGRF	258 (18 subsequent ACL injuries)	Males: 149 Females: 109	Males: 16.1 ± 1.6 Females: 16 ± 1.7	N/A	Basketball and volleyball	Elite	180° change of direction	ACLR: 18.7 ± 1.3 Control: 20.6 ± 2.7 (p=0.03)
(Leppänen et al., 2016)	Prospective ACL injury study- vGRF	171 (15 subsequent ACL injuries)	unreported	15.4 ± 1.9	N/A	Basketball and floorball	elite	Double leg drop jump 30cm box	ACLR: 1347 ± 403 Control: 1083 ± 321 (p<0.01)
(King et al., 2019)	Retrospective study 9 months post ACLR	156 ACLR 62 Controls	Males: 156 Females: 0	ACLR: 24.8 ± 4.2 Control: 24.7 ± 3.9	0.8 ± 0.1	Field-sport	recreational	Unplanned 90° CoD	ACLR limb demonstrates reduced vGRF Asymmetry ACLR= 1.1± 0.6Nm/kg & Controls=0.5 ± 0.4Nm/kg (p<0.05)
								Single leg drop jump	ACLR limb demonstrates reduced vGRF Asymmetry ACLR= 2.7± 0.9Nm/kg & Controls= 1.5 ± 0.8Nm/kg (p<0.05)
Medial GRF									
(King et al., 2019)	Retrospective study 9 months post ACLR	156 ACLR 62 Controls	Males: 156 Females: 0	ACLR: 24.8 ± 4.2 Control: 24.7 ± 3.9	0.8 ± 0.1	Field-sport	recreational	Unplanned 90° CoD	ACLR limb demonstrates reduced mGRF Asymmetry ACLR= 0.3± 0.2Nm/kg & Controls= 0.2 ± 0.1Nm/kg (p<0.05)
								Planned 90° CoD	ACLR limb demonstrates reduced mGRF

									Asymmetry ACLR= 0.3± 0.1Nm/kg & Controls= 0.2 ± 0.1Nm/kg (p<0.05)
								Double leg drop jump	ACLR limb demonstrates increased mGRF Asymmetry ACLR= 0.14±0.1Nm/kg & Controls= 0.09 ± 0.1Nm/kg (p<0.05)
Posterior GRF									
King (2019)	Retrospective study 9 months post ACLR	156 ACLR 62 Controls	Males: 156 Females: 0	ACLR: 24.8 ± 4.2 Control: 24.7 ± 3.9	0.8 ± 0.1	Field-sport	recreational	Planned 90° CoD	ACLR limb demonstrates reduced pGRF Asymmetry ACLR= 0.2± 0.1Nm/kg & Controls= 0.2 ± 0.1Nm/kg (p<0.05)
								Single leg drop jump	ACLR limb demonstrates reduced pGRF Asymmetry ACLR= 0.12±0.1Nm/kg & Controls= 0.06 ± 0.1Nm/kg (p<0.05)

Abbreviations: ACLR= anterior cruciate ligament reconstruction, DL= double leg, CoD= change of direction, GRF=ground reaction force, vGRF= vertical ground reaction force, mGRF= medial ground reaction force, pGRF= posterior ground reaction force, shading of cells= significant difference with p<0.05

2.14 Summary of literature review

Chapter 2 evaluated the current evidence surrounding sensorimotor dysfunction following ACLR and the potential implications for ACLR reinjury risk. In particular, there was a focus on the role somatosensory and visual systems played in effective motor control. ACL injuries continue to be common in multidirectional field-based sports (Pulici et al., 2023) and result in extended rehabilitation and return to sport timelines for athletes. Even after extensive rehabilitation, ACLR reinjury rates have remained unchanged over the years (Arundale et al., 2018; Engebretsen et al., 1990; Lai et al., 2018b; Sandon et al., 2020). Whilst ACLR focuses on reconstructing the mechanical stability that the ACL provides, it is the substantial proprioceptive input that the ACL provides which may be negatively affected from ACL injury and subsequent ACLR (Dhillon et al., 2012; Dhillon et al., 2010). The disruption to the proprioceptive input may lead to over reliance on the visual system during movement and this may be a reason why reinjury rates have remained unchanged, although the overall level of evidence for this is low (Grooms et al., 2015a; Swanik, 2015).

ACL injuries are predominantly non-contact in nature and occur within 70 milliseconds of ground contact which suggests that sensorimotor influences on motor planning and execution should be considered (Boden et al., 2000; Sundberg et al., 2025). The evidence currently demonstrates small but statistically significant proprioceptive deficits following ACLR (Vitharana et al., 2024). There is also evidence via functional brain MRI and EEG that central reorganisation of the sensorimotor centres occurs with increased activation of the visual cortical areas during movement (Grooms et al., 2017; Criss et al., 2020), thereby suggesting that motor planning centres have reweighted to rely more on the visual system. There are several limitations with the current literature. The first being that the studies utilising functional brain MRI and EEG has participants completing non-weightbearing and simple movements such as knee flexion/extension (Grooms et al., 2017). Yet, ACL injuries occur during high velocity and high

loading movements, therefore future research is required at either assessing cortical activation during these movements or assessing the biomechanics of participants during high loading tasks (such as CoD) who have been identified as being visually reliant. Another limitation of the current literature is that clinical balance testing has consistently failed to detect VR in ACLR cohort which may suggest that current tasks do not challenge the sensorimotor system sufficiently (Wikstrom et al., 2017). A third limitation of the literature is that the relationship between VR and ACLR reinjury remains speculative with only one case study linking VR to ACLR reinjury (Grooms et al., 2015c).

Visual processing abilities have been suggested to have an influence on ACL injury risk but the current literature remains inconclusive due to small sample sizes and heterogeneity in the assessment tools utilised (Swanik, 2015; Herman and Barth, 2016). A single prospective study in uninjured college athletes indicated that those sustained an ACL injury had poorer visual memory, poorer visual processing speed and slower reaction times than those who did not sustain an ACL injury (Swanik et al., 2007).

In summary, the literature review demonstrates that ACL injury and subsequent ACLR results in persistent reorganisation of the afferent systems. This leads to ACLR athlete's becoming VR for motor planning and execution. However, how VR influences an ACLR athlete's biomechanics is unclear as there is no research investigating this relationship. This presents a gap in our current understanding of VR and reinjury mechanisms. Therefore, this formed the central justification for the investigations presented in this thesis with the main aim being to examine whether VR negatively affects ACLR athletes' unplanned CoD biomechanics.

Chapter 3

The reliability of a stepdown task to assess for the weighting of visual information during a motor task.

3.1 Abstract

Context

Visual reliance has been suggested to occur following musculoskeletal injury such as anterior cruciate ligament reconstruction and chronic ankle instability. Clinical testing is currently limited to single leg balance as there is a lack of access to functional brain MRIs and electroencephalograms. However, a single leg balance test appears unable to differentiate between those with visual reliance in the anterior cruciate ligament reconstructed (ACLR) population. Therefore, a stepdown task (blinded versus full vision) was utilised to derive a visual reliance (VR) index as it is higher loading than stationary standing without being too difficult for participants to complete.

Objective

To investigate whether a VR index derived from a stepdown task under two visual conditions (full vision and blinded) was reliable. The study would also determine the reliability of a stepdown task both blinded and with full vision individually.

Design

Cross-sectional study

Setting

Clinical Laboratory

Patients or Other Participants

15 healthy and active participants (5 females, 10 males, age= 26.2±3.8 years, height=172.9±7.5cm, mass=73.7±10.6kg, & tegner scale 6.8).

Main Outcome Measure(s)

The VR index was calculated utilising the time to stability when both blinded and with full vision. Time to stability was calculated over three different directions (medial-lateral[ML], anterior-posterior[AP] and resultant) and two different time periods (5 seconds and 10 seconds) to identify if there was a difference in reliability. The task was also completed on both dominant and non-dominant legs.

Results

Overall, there was good-to-excellent reliability for the visual reliance index for in the ML direction (ICCs 0.64-0.94) and resultant (ICCs 0.80-0.97). The VR index had poor reliability in the AP direction during the 5 second analysis but good-to-excellent reliability over the 10 second time period (ICCs 0.76-0.92). The reliability of the time to stability measure when blinded and full vision was good-to-excellent in all three directions (ICCs 0.75-0.96) except for the 10 second AP direction and the resultant.

Conclusion

The VR index demonstrated good-to-excellent reliability for all directions for both the 5 and 10 second analysis, except in the 5 second AP calculation.

Key words

Visual reliance, time to stability, reliability, stepdown

Key Points

- The visual reliance index derived from the stepdown task demonstrated good-to-excellent reliability.

- This was the first study to demonstrate that the stepdown test can be reliably completed when blinded.

3.2 Introduction

Motor control is a fundamental function for human movement and athletic performance (Atasavun Uysal and Düger, 2020). It refers to the processes involved in motor planning and execution, maintaining postural control and maintaining joint stability throughout movement (Ivanenko and Gurfinkel, 2018b; Riemann and Lephart, 2002a; Massion, 1994). The sensorimotor system is central to effective motor control (Riemann and Lephart, 2002a) and consists of three elements: (1) all of the sensory systems (e.g. somatosensory, visual, vestibular) to gain information about the environment and the body's posture within it, (2) motor planning centres to process the sensory information and generate a motor response, and (3) the efferent system to activate muscles to perform the desired motor response (Riemann and Lephart, 2002a; Riemann and Lephart, 2002b; Craighero, 2022). It is thought that sensorimotor dysfunction may result in injuries due to altered motor control (Chmielewski et al., 2021; Grooms et al., 2015c; Swanik, 2015).

Sensorimotor dysfunction can occur following an injury to the musculoskeletal system (Grooms et al., 2015a; Chmielewski et al., 2021). One such form of dysfunction is an increased reliance on visual information for motor control (Grooms et al., 2015a), which can occur in response to altered information from the somatosensory system due to the presence of pain and damage of mechanoreceptors following soft tissue injury (muscle, cartilage, ligament and bone) (Neto et al., 2019b). This has been reported to occur following anterior cruciate ligament reconstruction (ACLR) (Grooms et al., 2017) and chronic ankle instability (CAI) (Kim, 2020a). Several studies in the ACLR population have recently demonstrated, utilising functional brain MRI, increased activity in the brain centres concerned with visual information processing during a simple motor task

(supine knee extension and flexion), as compared to healthy controls (Criss et al., 2020; Lehmann et al., 2021b; Grooms et al., 2017). This has also been replicated in CAI individuals via the analysis of energy consumption in the brain centres (Rosen et al., 2019; Xie et al., 2022). Increased reliance on visual information for motor control has been suggested to increase the risk of reinjury in ACLR individuals (Grooms et al., 2015c) which highlights the importance for clinicians to be able to identify individuals at risk. A limitation of the work to date is that many of the outcome measures used to identify visual reliance is technology that is not accessible to clinicians (eg. functional brain MRI and electroencephalogram), so more research is required for clinical tests to identify visual reliance.

Clinical testing to identify increased reliance on the visual system is predominantly in the form of balance testing under varying conditions of vision (Kouvelioti et al., 2015; Lehmann et al., 2017; Wikstrom et al., 2017). The most common test used by clinicians is single leg standing with full vision and then whilst blind-folded (Kim, 2020b). The difference between performance under the two visual conditions determines how reliant the individual is on visual information. Whilst this test has been able to demonstrate differences between healthy controls and those with CAI (Kim, 2020b; dos Santos et al., 2014), it has failed to show differences between healthy controls and the ACLR population (Wikstrom et al., 2017). This is despite functional brain MRI and electroencephalograms demonstrating that ACLR individuals are more reliant on the visual systems. The difference in these findings between those with CAI and ACLR may be the result of the task not challenging the sensorimotor system enough to elicit a shift to visual reliance. Also, during a simple single-leg static balance task, individuals rely predominantly on an ankle-strategy rather than rely on knee control (Nashner and McCollum, 1985).Time to stability is a measure utilised to quantify an athlete's performance in reaching a stable state following a jump or hop (Fransz et al., 2015). A greater time to stability indicates a poorer ability in controlling posture upon landing. There is large heterogeneity within the literature when assessing time to stability in

ACLR cohorts with tasks including a stepdown task (Colby et al., 1999; Byrne et al., 2021) or a single leg landing following a double leg jump (Webster and Gribble, 2010; Chaput et al., 2021a). Similarly, there is heterogeneity regarding the time athletes are required to remain stable after landing with studies ranging from 3 seconds to 10 seconds (Byrne et al., 2021; Colby et al., 1999; Webster and Gribble, 2010; Chaput et al., 2021a). The length of time athletes are required to remain stable has an effect on time to stability results, with a longer stable time requirement resulting in a longer time to stability measurement (Fransz et al., 2015). A longer stable time requirement may result in a more reliable time to stability measure, as it allows for the athletes remain account for the initial ground reaction force from the impact of landing but further investigation is required.

Athletes sustain ACL injuries during non-contact high loading tasks such as sudden decelerations, change of direction and landing from a jump (Boden et al., 2000). Therefore, assessing visual reliance during a high loading task may have greater construct validity than static balance tasks. A stepdown task examining time to stability, adapted from Colby and colleagues (1999)(Colby et al., 1999), may be more appropriate due (i) to higher loading, and (ii) performing the task with blinded vision is not dangerous for ACLR participants. While this task has previously been demonstrated to be highly reliable when performed with full vision amongst healthy participants and those with ACLR (Colby et al., 1999), it has not been examined in the blinded condition or in the comparison of full versus blinded vision.

Time to stability is a measure utilised to quantify an athlete's performance in reaching a stable state following a jump or hop (Fransz et al., 2015). A greater time to stability indicates a poorer ability in controlling posture upon landing. There is large heterogeneity within the literature when assessing time to stability in ACLR cohorts with tasks including a stepdown task (Colby et al., 1999; Byrne et al., 2021) or a single leg landing following a double leg jump (Webster and Gribble, 2010; Chaput et al., 2021a). Similarly, there is heterogeneity regarding the time athletes are required to remain stable after landing with studies ranging from 3 seconds to 10 seconds (Byrne et al., 2021;

Colby et al., 1999; Webster and Gribble, 2010; Chaput et al., 2021a). The length of time athletes are required to remain stable has an effect on time to stability results, with a longer stable time requirement resulting in a longer time to stability measurement (Fransz et al., 2015). A longer stable time requirement may result in a more reliable time to stability measure, as it allows for the athletes remain account for the initial ground reaction force from the impact of landing, but further investigation is required.

Therefore, the aim of this study was to examine the reliability of a visual reliance index derived from the stepdown test (blinded vision versus full vision). A further aim of the study was to determine the reliability of the stepdown task when performed with blinded vision and full vision. A tertiary aim was to determine if there were any differences in reliability between a 5 second and 10 second stable time requirement.

3.3 Methods

Participants

A repeated measures design was utilised with participants re-tested five to seven days following their first testing session. Participants were recruited locally and were to be free of lower limb injury in the previous two years. Participants had no history of neurological disease, visual injury, vestibular injury or orthopaedic surgery. The participants completed the Tegner Activity scale to determine their level of sport-based activity. The study was approved by the ethics and research committee of the UPMC Sports Surgery Clinic, Dublin, Ireland (protocol assigned number APMOC9102CSSIVHT). A priori power analysis was conducted utilising 'Sample size calculator (web)' (Arifin, 2025). 11 participants were required when an expected ICC value of 0.9, minimum acceptable ICC value of 0.5, significance level of 0.05 and power at 80% were required (Colby et al., 1999).

Procedure

The tests were administered by the same clinician (TV). Time to stability measures were obtained under two conditions: (1) full vision in which the participants eyes were open, and (2) blinded vision in which the participants wore an eye mask to obscure vision. Partial obstruction of vision has been previously utilised via the use of stroboscopic glasses (Kim et al., 2017b; Harper et al., 2024). However, the literature is mixed with stroboscopic glasses being demonstrating a similar effect on some balance variables as being completely blinded and then a significant difference to being completely blinded when assessing other balance (Harper et al., 2024). Therefore, it was chosen to have participants have no vision during one of the conditions via the use of blindfold to get clearer results. The stepdown task was adapted from Colby and colleagues (1999). Participants were barefoot. A 20cm step was placed behind dual force plates (1000Hz BP400600, AMTI, USA). Participants placed their hands on their hip and stepped off the step with a single leg and upon landing on the force plate, attempted to achieve stability as quickly as they could and maintain this position for 20 seconds. The landing posture of the leg was not standardised for trials; participants were allowed to adopt a strategy that suited them. Participants were asked to keep their head up and their eyes looking forwards. Three trials were completed for each leg (dominant [DM] and non-dominant [NDM] in each condition (full vision and blinded vision), with two warmup trials provided for each leg. A maximum of six trials were allowed for each leg under each condition, so that participants had the best opportunity of attaining three valid trials without fatigue becoming a limiting factor.

Trials were deemed invalid if the participants removed their hands from their waist, placed their non-testing leg on the ground, shuffled the testing foot on the force plate after landing or removed their blindfold during trial.

Data processing

The data for each trial were recorded using native software, Netforce (AMTI, USA) for the force plates. The data were exported to Matlab for further processing utilising a customised code. A sequential estimation method was used to determine time to stability (TTS) (Colby et al., 1999). Two threshold times (5 seconds and 10 seconds) were used to explore if they affected reliability. To undertake sequential estimation, a cumulative average trace was calculated on vertical, anterior-posterior (AP) and medial-lateral (ML) force traces separately. Upper and lower bounds were calculated for all directional forces; upper and lower bounds were defined as the mean (μ) of the force trace plus and minus the standard deviation (σ) multiplied by 0.25, respectively (Colby et al., 1999).

$$upper\ bound = \mu + 0.25\sigma$$

$$lower\ bound = \mu - 0.25\sigma$$

Ground contact was determined as the point in which the vertical ground reaction force surpassed 20N. The TTS was then determined as the last point at which the cumulative trace crossed either the upper or lower bounds and remained within the bounds (Figure 3.3).

TTS measures were taken for each trial in both the AP and ML directions. A resultant TTS was also calculated utilising the combined AP and ML values(Webster and Gribble, 2010):

$Resultant\ TTS = \sqrt{APTTS^2 + MLTTS^2}$.

The visual reliance (VR) index was calculated separately for each of the three TTS measures (AP, ML and resultant):

$$VR\ index = \left(\frac{[TTS\ (blinded) - TTS\ (full\ vision)]}{TTS\ (full\ vision)}\right)\ x\ 100$$

With regards to the VR index, a negative score indicates the participants achieved stability quicker when blinded as opposed to a positive score indicating a longer TTS when blinded.

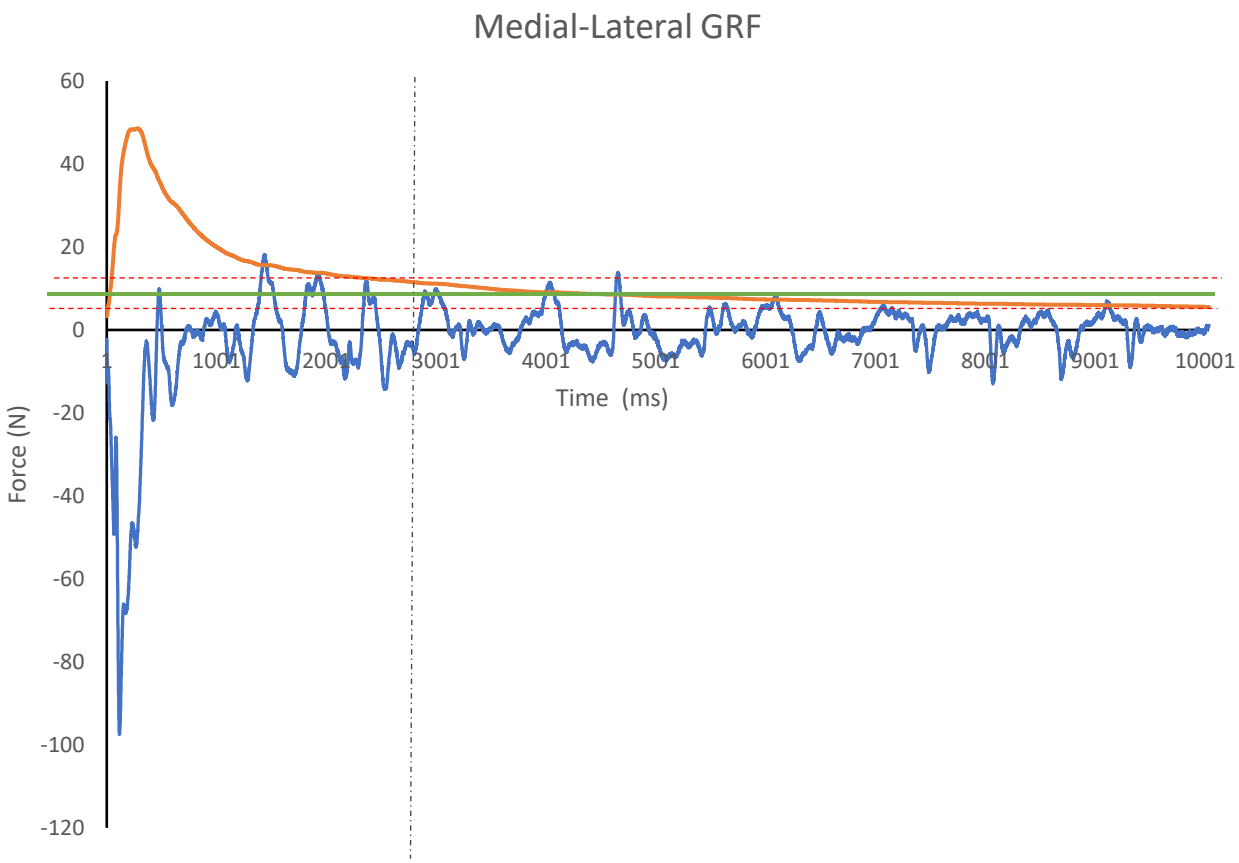


Figure 3.3. Calculation of time to stability via sequential estimation. Solid blue line represents medial-lateral ground reaction force and the solid orange line represents sequential estimation of ground reaction force. Time to stability is symbolised by the vertical dashed line. Red dashed horizontal lines represent the upper and lower bounds. The solid green horizontal line represents mean of the ground reaction force.

Statistical Analysis

The mean of three trials of TTS for each direction separately (AP, ML and resultant) and for each visual condition (blinded, full vision and visual reliance index [VR index])) was used for statistical analysis. Alpha level was set at 0.05 for all statistical analyses. Statistical analyses were conducted in SPSS (Version 27, IBM Corp, Armonk, NY). Reliability was assessed using two-way random effects model of intraclass correlation coefficient ($ICC_{2,3}$). 95% confidence intervals (CIs) were calculated for each ICC. ICCs were classified as less than 0.5 as poor, 0.5-0.75 as moderate, 0.75-0.90 as good, and greater than 0.90 as excellent (Koo and Li, 2016).

To determine if significant differences were evident between 5 and 10 seconds analyses, paired t-tests were performed.

Standard error of the mean (SEM) was calculated as:

$$SEM = Standard\ deviation_{pooled}\ x\ \sqrt{(1 - ICC}$$

SEM percentage was calculated as:

$$SEM\ \% = \left(\frac{SEM}{mean_{pooled}}\right) x\ 100$$

Minimal detectable change (MDC) was calculated to allow clinicians to identify when a change is clinically different between two measurements:

$$MDC = SEMx\ 1.96\ x\ \sqrt{2}$$

3.4 Results

Fifteen healthy participants (5 females, 10 males, age= 26.2 ± 3.8 years, height= 172.9 ± 7.5cm, weight= 73.7 ± 10.6, & Tegner scale 6.8; see table 3.4.A) completed the testing. All healthy controls were able to complete the task in both full vision and blinded vision conditions. The time to stability measure and ICC values are presented in table 3.4.B.

Table 3.4.A. Participant Demographics. Mean Values Presented with Standard Deviation (SD)

	Male (SD)	**Female (SD)**	**Total (SD)**
Number of participants	10	5	15
Age (years)	26.2 (3.8)	24.4 (0.5)	25.6 (3.2)
Height (cm)	175.8 (7.6)	167.2 (1.9)	172.9 (7.5)
Mass (kg)	80.3 (4.9)	60.6 (4.4)	73.7 (10.6
Tegner score	7	6.4	6.8

Time to stability (Table 3.4.B)

Time to stability measures for all three directions (AP, ML and the resultant) were significantly longer for the 10 second analysis as compared to the 5 second analysis for both legs and under both blinded and full vision conditions ($p<0.001$).

For the 5 second analysis, the blinded conditions demonstrated significantly shorter TTS for both limbs in the ML direction (NDM t= -3.80 $p<0.001$; & DM t= -4.55 $p<0.001$) and the resultant (NDM t= -3.87 $p<0.001$; & DM t= -4.26, $p<0.001$). No significant difference was evident between visual conditions in the AP direction (NDM t=0.46 p=0.32; & DM t=1.26 p=0.11). Similarly, for the 10 seconds analysis, the blinded conditions demonstrated significantly shorter TTS than the full vision conditions in the ML direction (NDM t= -7.39 $p<0.001$; & DM t= -5.09 $p<0.001$) and for the resultant (NDM t= -6.12 $p<0.001$; & DM t= -4.21 $p<0.001$). No significant difference was evident between visual conditions when measured in the AP direction (NDM t=0.22 p=0.42; & DM t= -0.42 p=0.34).

The VR index was significantly greater in the negative direction for the NDM leg mediolaterally and for the resultant, when assessed for 10 seconds compared to 5 seconds (NDM: ML t= 4.94 $p<0.001$; & t=4.87 $p<0.001$). Contrastingly, anterior-posteriorly, the 10 second VR index was significantly greater in the positive direction (NDM: AP t= -7.90 $p<0.001$). However, no significant difference in the VR index was present for the DM leg in the any direction when comparing 10 seconds and 5 seconds calculations.

Table 3.4.B. Time to Stability (TTS) Values and Corresponding Intraclass Coefficients (ICCs) Values for the 5 and 10 Seconds Analysis

Condition	**TTS (5s)**						**TTS (10s)**					
	ML		**AP**		**Resultant**		**ML**		**AP**		**Resultant**	
	Mean (SD)	ICC (CI 95%)	Mean (SD)	ICC (CI 95%)	Mean (SD)	ICC (CI 95%)	Mean (SD)	ICC (CI 95%)	Mean (SD)	ICC (CI 95%)	Mean (SD)	ICC (CI 95%)
NDM blinded vision (s)	2.19 (0.09)	**0.93*** (0.80-0.98)	2.75 (0.06)	**0.79*** (0.05-0.94)	3.54 (0.07)	**0.90*** (0.72-0.97)	3.19 (0.20)	**0.94*** (0.82-0.98)	4.55 (0.09)	**0.83*** (0.42-0.95)	5.59 (0.11)	**0.96*** (0.87-0.99)
NDM full vision (s)	2.45 (0.11)	**0.93*** (0.78-0.98)	2.74 (0.04)	**0.91*** (0.72-0.97)	3.69 (0.08)	**0.91*** (0.73-0.97)	4.03 (0.16)	**0.93*** (0.81-0.98)	4.54 (0.06)	**0.96*** (0.87-0.99)	6.09 (0.10)	**0.95*** (0.85-0.98)
DM blinded vision (s)	2.25 (0.16)	**0.82*** (0.46-0.94)	2.76 (0.05)	**0.86*** (0.59-0.95)	3.58 (0.11)	**0.81*** (0.43-0.94)	3.42 (0.41)	**0.75*** (0.24-0.92)	4.55 (0.20)	0.31 (-1.11-0.77)	5.77 (0.39)	0.18 (-1.64-0.73)
DM full vision (s)	2.51 (0.08)	**0.88*** (0.66-0.96)	2.75 (0.04)	**0.88*** (0.66-0.96)	3.73 (0.06)	**0.93*** (0.76-0.98)	4.05 (0.13)	**0.94*** (0.81-0.98)	4.57 (0.08)	**0.87*** (0.60-0.96)	6.12 (0.12)	**0.93*** (0.79-0.98)
NDM V-M index (%)	-8.94 (5.27)	**0.88*** (0.66-0.96)	0.33 (1.87)	0.48 (-0.25-0.81)	-4.02 (1.20)	**0.97*** (.091-0.99)	-20.17 (5.25)	**0.91*** (0.74-0.97)	0.68 (1.05)	**0.92*** (0.76-0.97)	-7.78 (1.25)	**0.97*** (0.93-0.99)
DM V-M index (%)	-10.00 (8.65)	**0.64*** (-0.01-0.88)	0.66 (2.14)	0.26 (-1.42-0.76)	-4.23 (1.74)	**0.92*** (0.77-0.97)	-15.71 (9.13)	**0.72*** (0.18-0.91)	0.00 (1.80)	**0.76*** (0.29-0.92)	-6.02 (2.58)	**0.80*** (0.41-0.93)

Abbreviations: *TTS*= time to stability, *s*= seconds, *SD*= standard deviation, *V-M index*= visual-motor index, *ML*= medial to lateral, *A*P= anterior to posterior, *= significance level equal or less than 0.05

Table 3.4.C. Standard Error of Measurement (SEM) and Minimal Detectable Change (MDC) for Dominant (DM) and Nondominant (NDM) Legs During Full Vision and Blinded Vision Conditions with 5 and 10 Seconds Analysis of Stepdown Task

Condition	**TTS (5s)**									**TTS (10s)**								
	ML			**AP**			**Resultant**			**ML**			**AP**			**Resultant**		
	SEM	SEM (%)	MDC	SEM	SEM (%)	MDC	SEM	SEM (%)	MDC	SEM	SEM (%)	MDC	SEM	SEM (%)	MDC	SEM	SEM (%)	MDC
NDM blinded vision (s)	0.08	3.7	0.21	0.05	1.8	0.14	0.06	1.7	0.17	0.16	5.0	0.45	0.08	1.8	0.23	0.08	1.4	0.23
NDM full vision (s)	0.09	3.7	0.26	0.04	1.5	0.11	0.17	4.6	0.20	0.15	3.7	0.42	0.05	1.1	0.14	0.09	1.5	0.25
DM blinded vision (s)	0.14	7.6	0.38	0.05	1.8	0.13	0.09	2.5	0.25	0.42	12.3	1.15	0.26	5.7	0.73	0.46	8.0	1.28
DM full vision (s)	0.10	4.0	0.27	0.04	1.5	0.11	0.06	1.6	0.17	0.12	3.0	0.33	0.08	1.8	0.22	0.10	1.6	0.28
NDM V-M index (%)	6.02		16.69	2.07		5.73	1.00		2.77	4.54		12.60	1.10		3.06	1.13		3.13
DM V-M index (%)	7.78		21.56	2.59		7.17	1.39		3.85	8.90		24.66	1.95		5.41	2.50		6.92

Abbreviations: *TTS*= time to stability, *s*= seconds, *SEM*= standard error of measurement, *MDC*= minimal detectable change, *NDM*= nondominant, *DM*= dominant, *V-M* index= visual-motor index, *ML*= medial to lateral, *A*P= anterior to posterior

Intraclass coefficients (Table 3.4.B)

In the ML direction, TTS measures utilising 5 seconds demonstrated good-to-excellent reliability for both the NDM and DM legs under both visual conditions (NDM blinded vision p<0.001, NDM full vision p<0.001, DM blinded vision p=0.002, DM full vision p<0.001). Similarly, the 10 second analysis demonstrated good-to-excellent reliability for all conditions (NDM blinded vision p<0.001, NDM full vision p<0.001, DM blinded vision p=0.009, DM full vision p<0.001). The VR index derived for each leg in the ML plane demonstrated moderate reliability for the DM leg (DM 5 seconds p=0.03, & 10 seconds p=0.01) whilst the NDM leg achieved good-to-excellent reliability (NDM 5 seconds p<0.001, 10 seconds p<0.001).

In the AP direction, TTS measures demonstrated mixed reliability during both 5 and 10 seconds analyses. For 5 seconds, the reliability for each leg under both visual conditions demonstrated excellent reliability (p<0.001). For 10 seconds, the reliability for the NDM leg (blinded and full vision) and DM leg (full vision) demonstrated good-to-excellent reliability, whilst the DM blinded vision had poor reliability (NDM blinded vision p<0.001, NDM full vision p<0.001, DM blinded vision p=0.25, DM full vision p<0.001). The reliability for the VR index was not significant for either leg during the 5 seconds analysis (NDM VR index p=0.07, DM VR index p=0.30) but had significantly good-to-excellent reliability for the 10 seconds analysis (NDM VR index p<0.001, DM VR index p=0.006)

The TTS measures utilising the resultant measure demonstrated good-to-excellent reliability for the 5 second analysis for both NDM and DM legs, for blinded and full vision (NDM blinded vision p<0.001, NDM full vision p<0.001, DM blinded vision p=0.002, DM full vision p<0.001). During the 10 second analysis, the NDM leg (blinded and full vision) and the DM leg with full vision demonstrated good-to-excellent reliability (NDM blinded vision p<0.001, NDM full vision p<0.001,

DM full vision p<0.001). However, the DM leg with blinded vision demonstrated poor reliability (DM blinded vision p=0.36). The VR index for both 5 and 10 seconds analyses demonstrated good-to-excellent reliability for both DM and NDM legs (5 seconds NDM p<0.001 and DM p<0.001, 10 seconds NDM p<0.001 and DM p=0.003).

Standard error of measurement and minimal detectable change (Table 3.4.C)

The SEM and MDC for all of the variables are listed in table 3.4.C. The SEM (%) amongst both NDM and DM legs for the 5 seconds analysis ranged from 1.5-7.6%, whilst the 10 seconds analysis was 1.1-12.3%. With regards to the VR index during 5 second analysis, SEM ranged from 2.8-7.8%, whilst the SEM for 10 seconds analysis ranged from 3.1-8.9%. The MDC for the 5 seconds analysis of the NDM and DM limbs ranged from 0.11-0.38 seconds, whilst for 10 seconds it ranged from 0.14-1.28 seconds. The MDC for the VR index for the 5 seconds analysis ranged from 2.8-21.6%, whilst the MDC for 10 seconds ranged from 3.1-24.7%.

3.5 Discussion

The aim of the study was to examine the reliability of a visual reliance index derived from the stepdown test (blinded vision versus full vision). Further aims of the study were: (1) to determine the reliability of the stepdown task when performed with blinded vision and full vision and (2) to determine if there were any differences in reliability between a 5 second and 10 second stable time requirement. The findings indicate that both 5 and 10 second analysis demonstrated good-to-excellent reliability for the NDM and DM limbs under both visual conditions (ICCs> 0.75), except for the DM limb in the AP direction and the resultant when measured over 10 seconds. The VR index demonstrated moderate-to-excellent reliability in all directions and for both time periods (5 and 10 seconds), except for the AP direction during a 5 second analysis. A potential

reason for the latter low reliability is because the stepping down task requires the participant to control forward momentum, which may influence AP movement greater than ML movement. Hence, as the time period analysed increases to 10 seconds, the reliability of the VR index in the AP plane improves (ICCs: DM=0.76 and NDM=0.92) as the effect of the forward momentum variations caused by changes in initial contact are attenuated. In summary, when using the stepdown test, data from the ML direction with analyses of 5 or 10 seconds may be better than the AP direction when assessing for visual reliance.

The SEM and MDC indicate the extent to which clinicians are able to determine a true change in an individual's measurement as opposed to random measurement error (Furlan and Sterr, 2018). The SEM (%) for each leg, under both visual conditions and for the VR index, was less than 10%; indicating that the test set-up can be completed with acceptable measurement error (Hopkins, 2000). Clinicians utilising the test are able to determine an improvement or decline in performance for an individual in the clinic if their TTS measure changes greater than the MDC (Table 2).

Assessing TTS in the absence of vision can be used to determine how well an individual is able to utilise proprioceptive and vestibular information to maintain postural control (Karmali et al., 2021; Lee and Park, 2022). This is the first study to examine TTS measures with a stepdown task with participants blinded. Previous research examining a stepdown task whilst blinded have only utilised a qualitative assessment of balance by the examiners and demonstrated poor-to-good agreement between raters (kappa coefficient= 0.10-0.8) (Thelen et al., 2017; Park et al., 2013). The ICCs of the blinded conditions in our study demonstrated good-excellent reliability (ICCs= 0.75-0.96), except during the 10 second analysis of the DM in the AP direction and the resultant. The resultant TTS utilises the outcome from the AP direction, so the poor reliability in the AP direction will negatively affect the resultant reliability. This suggests that clinicians utilising this stepdown test when using blinded participants, should predominantly focus on the ML variables.

Assessing TTS with full vision allows clinicians to determine how well an individual utilises their motor control systems to attain stability. Our study is not the first study to utilise the stepdown task when participants had full vision. Our study demonstrated slightly better reliability (ICCs= 0.87-0.96) compared to previous studies examining the stepdown task with full vision (ICCs=0.56-0.87) (Byrne et al., 2021; Colby et al., 1999). Other studies utilising the stepdown task for TTS demonstrate a large range in the times reported due to differences in the way the data is collected, such as the sampling rate of force plate (greater sampling rate may lead to longer TTS) or the time required for participants to remain still on the force plate (longer static time will result in longer TTS measurement when using sequential estimation)(Byrne et al., 2021; Colby et al., 1999; Naserpour et al., 2018; Wikstrom et al., 2005). Byrne and colleagues (2021) utilised a similar ten second hold time on the force plate for their participants. They reported TTS measures of 6.16-7.49 seconds in healthy controls (Byrne et al., 2021) which is similar to the findings of our study when examining a ten second hold time. . The results of our study demonstrate time to stability measures within the ranges of the four studies which would suggest that our protocol is appropriate.

Clinical relevance

Visual reliance may occur following musculoskeletal injuries such as lateral ankle sprains and ACL injuries (Grooms et al., 2015a; Kim, 2020b). The lateral ankle ligaments and ACL are densely innervated with proprioceptors which provide proprioceptive information to the motor control centres (Çabuk and Kuşku Çabuk, 2016; Gomez-Barrena et al., 1996; Raunest et al., 1998). However, following injury to these ligaments there is a loss of the proprioceptors within the ligament. This leads to altered or absent information in motor control centres when planning a motor task. Therefore, the motor control centres become more reliant on visual information to compensate for the altered proprioceptive information. This has been demonstrated on

functional brain MRIs and EEGs in the ACLR population (Criss et al., 2020; Grooms et al., 2017; An et al., 2022). Clinically, single leg balance with eyes open vs eyes closed, has been used to identify visual reliance. However, its reliability is mixed (ICCs= 0.53-0.96) (Kouvelioti et al., 2015; Troester et al., 2018) and has similar declines in stability when blinded occurs in the ACLR population and healthy controls which suggests that the task does not stress the motor control centres enough to demonstrate visual reliance in the ACLR population (Wikstrom et al., 2017). Therefore, higher loading tasks may be required to sufficiently stress the motor control centres to identify visual reliance in the ACLR population. TTS measures taken when participants completed a single leg land following double leg jump (jumping 50% of their max jump height) has previously demonstrated that ACLR participants take longer to stabilise than healthy controls when their full vision is present (Webster and Gribble, 2010). However, as this task cannot be completed blinded during due to safety concerns, it cannot be to determine if ACLR increases visually reliance. Therefore, given the high reliability for the VR index (and both eyes closed and eyes open) for our stepdown task that induces higher loading than single leg standing but is less dangerous than jumping/landing blindfolded, suggests that it may be used in the ACLR population in the future.

Limitations

This study only examined uninjured participants, future research will need to determine if the stepdown task is reliable in injured populations, such as ACL injured athletes. ACL injured athletes post-surgery spend 9-12 months in rehabilitation, so reliability for the stepdown task would need to be completed along this time period to determine at what stage measures are reliable. Another limitation of the study is that the order of the trials (full vision and blinded vision) was not randomised. This may potentially result in improved performance due to practice or order effect. However, to minimise this, when completing trials within a particular visual condition, the participants were provided with warm up trials and then trials would alternate between legs.

3.6 Conclusion

The VR index derived in all 3 directions under both time periods (5 and 10 second analysis) demonstrates good-to-excellent reliability for the DM and NMD limbs except for the AP direction during the 5 second analysis. Clinicians may therefore utilise the stepdown test with a 10 second analysis as a reliable measure of an individual's visual reliance with particular focus on the ML direction. The stepdown task during 5 and 10 second analysis demonstrates good-to-excellent reliability for TTS measures for the NDM and DM limbs of healthy controls under both visual conditions (blinded and full vision) in all 3 directions (ML, AP and the resultant), except for the 10 second analysis of the DM limb when blinded in the AP direction and the resultant.

Link between Chapter 3 and 4

VR index score during the 10 second analysis of the stepdown task is reliable in all force directions (AP, ML and resultant), especially the ML direction. This provides a clinical test that can be applied to an ACLR population to determine if it is able to identify VR. Previous studies have utilised functional brain MRI and EEG to demonstrate that ACLR cohort have increased VR as represented by increased activity within the visual cortex and secondary somatosensory cortex during simple knee movements (Grooms et al., 2017; Criss et al., 2020; Lehmann et al., 2021a). Therefore, Chapter 4 will utilise the stepdown task in both a ACLR cohort and a healthy control cohort to determine if it is able to detect a difference between the two groups.

Chapter 4

Visual reliance in ACLR athletes 8 months post-surgery

4.1 Abstract

Background

Visual reliance (VR) can occur in athletes following anterior cruciate ligament reconstructions (ACLR) potentially affecting their motor control and increasing reinjury risk. Current identification of VR predominantly utilises functional brain MRI and electroencephalography, with limited clinic-friendly tests available to clinicians.

Hypothesis

ACLR athletes eight months post-surgery would exhibit greater VR during a stepdown task compared to an uninjured control group [group] and when comparing their injured to uninjured limbs [limb].

Study Design

Cross-sectional study

Methods

Ninety-two athletes (47 ACLR, 45 controls) completed: a stepdown task (eyes-open versus eyes-closed) on a force-plate, a joint position sense test and various self-reported knee function and fear questionnaires. A VR index score was derived from the stepdown test force data.

Results

There was a significant moderate and small interaction between limb and group on the VR index score in the medial-lateral and resultant directions. Simple main effects indicated a significant moderate and small effect size in medial-lateral and resultant directions, respectively; with the ACLR limb being more VR than the control dominant limb (medial-lateral: $F(1,90)= 8.36$, $p=0.005$, partial $\eta^2=0.085$, and resultant: $F(1,90)= 5.50$, $p=0.021$, partial $\eta^2=0.058$). There was also a significant large and moderate effect size between limbs within the ACLR group in medial-lateral and resultant directions, respectively (medial-lateral: $F(1,46)= 9.17$, $p=0.004$, partial $\eta^2=0.166$, and resultant: $F(1,46)= 7.13$, $p=0.010$, partial $\eta^2=0.134$).

No significant difference existed between group or limb for VR in the anterior-posterior direction and also joint position sense performance. No correlation existed between the questionnaires and VR index.

Conclusions

ACLR athletes demonstrated increased VR of the ACLR limb as compared to both their uninjured limb and healthy controls during a stepdown task. The medial-lateral direction being the most discriminative.

Clinical Relevance

The stepdown test can identify ACLR athletes who have VR and may require specific interventions.

4.2 Introduction

Anterior cruciate ligament (ACL) injuries are unfortunately common in multi-directional field sports and place a significant burden on athletes. ACL injuries can result in a large time loss for athletes (6 to 12 months of rehabilitation), carry a high risk of reinjury (Wiggins et al., 2016)

and not all athletes are able to return to preinjury level of sport (return to preinjury level of sport: 83% amongst elite athletes (Lai et al., 2018a) and 55% in recreational athletes (Kvist et al., 2005)).

ACL injuries occur predominantly with a non-contact mechanism during high loading and high velocity tasks, such as decelerations, landing from a jump and change of direction (Boden et al., 2000). A non-contact mechanism indicates that an athlete's movement strategy is a significant factor in sustaining an ACL injury (Bertelsen et al., 2017); therefore suggesting that errors in the athlete's motor control system may contribute to injury or re-injury of the ACL.

The sensorimotor system, which encompasses afferent systems (e.g. somatosensory and visual systems), efferent systems and the central processing of that information, is an essential component of the body's motor control system (Riemann and Lephart, 2002a). Dysfunction within the sensorimotor system may lead to errors in motor control (Swanik, 2015; Riemann and Lephart, 2002c). Given that ACL injuries and ACL reconstructions (ACLR) can lead to dysfunction within the sensorimotor system (Vitharana et al., 2024), there may be an increase in the risk of ACLR reinjury (Grooms et al., 2015c) as the ACL is richly innervated with proprioceptors which provide proprioceptive information to the sensorimotor system (Dhillon et al., 2012). An ACL injury and subsequent ACLR results in a loss of the proprioceptive information and in response to this, the sensorimotor system may place greater reliance on the visual system for motor control in recipients of ACLR (Grooms et al., 2015a; Chaput et al., 2021a). It has been suggested that increasing the reliance on the visual system may lead to increased neurocognitive burden on athletes, leading to errors in movement strategies when attempting to execute complex and reactive movements in chaotic sporting environments (Miko et al., 2021; Grooms et al., 2015a), thereby resulting in increased risk of ACLR reinjury (Grooms et al., 2015c; Swanik, 2015). Therefore, outcome measures to identify individuals with increased visual reliance may be pertinent in reducing the risk of ACLR reinjury.

Identifying visual reliance amongst athletes following ACLR has been predominantly conducted with methodologies such as functional brain magnetic resonance imaging (Grooms et al., 2017) and electroencephalograms (Chaput et al., 2021a; Lehmann et al., 2021a). These methods however are not readily available to clinicians, thereby preventing the identification of individuals at risk of (over) visual reliance. There is limited research investigating clinic-friendly tests that can be used in this population. One such study examined double leg landing mechanics during a double leg countermovement jump under varying visual conditions (full vision and stroboscopic vision) (Grooms et al., 2018). The study demonstrated increased knee flexion excursion of the ACLR and uninjured limbs in the ACLR cohort during stroboscopic vision as compared to full vision. This was contrasted by a reduction in knee flexion excursion in the uninjured control group. There was no other significant difference between groups for any other kinematic or kinetic measure. The findings of that study present some evidence of change in movement strategy under varying visual conditions, thereby potentially indicating a reliance on visual information. However, a limitation of the study is that it utilised a double leg task, so it is difficult to determine if any visual reliance is specific to motor planning relevant to only the ACLR limb.

Clinicians have commonly used single-leg balance tests under varying conditions of vision (eyes open versus eyes closed) to determine if athletes with ankle-based injuries are visually reliant (Kim, 2020a), with reduced performance when their eyes are closed being indicative of visual reliance (Kim, 2020a). However, this test does not appear appropriate in identifying ACLR individuals with visual reliance as healthy controls have similar decline in balance performance as ACLR individuals when their eyes are closed (Wikstrom et al., 2017). This may suggest that the task of single leg balance is not stressful enough for the knee-affected sensorimotor system as the task predominantly stresses ankle control (Horak and Nashner, 1986; Winter et al., 1998). Therefore, a balance task with higher loading of the knee (such as a single-leg stepdown task) may be required to determine if there is visual reliance in an ACLR cohort. An issue with higher loading tasks, is that an athlete's movement quality and performance can be adversely affected by factors

such as fear of reinjury/movement and fear of pain (Dudley et al., 2025; Paterno et al., 2018). Hence, factors such as fear of movement, fear of reinjury and self-reported knee function should be assessed during movement tasks.

The aim of this study was to determine if ACLR athletes are more visually reliant as compared to controls, utilising a single-leg stepdown task, at eight months post-surgery. A secondary aim was to determine if fear of movement, fear of reinjury, fear of the stepdown task or self-reported function negatively affected athletes' performance of the stepdown task.

4.3 Methods

ACLR and control athletes were recruited for this cohort study between November 2021 and August 2023. ACLR athletes were recruited from the list of four surgeons at the Sports Surgery Clinic, Dublin, Ireland (R.M., C.M., M.J., D.W.), whilst controls were recruited from advertisements in local sporting teams. The study received ethical approval from the Sports Surgery Clinic Ethics Committee (APMOC9102CSSIVHT) and was registered with ClinicalTrials.gov (NCT05121857).

Participants and setting

Ninety-two male participants aged between 18 and 36 years of age were included in the study. ACLR participants were included if they played a multidirectional field-based sport and intended to return to the same level of sport or higher. All ACLR participants underwent primary ACLR with either a bone-patellar tendon-bone or quadriceps tendon graft. Participants who had concomitant ligament repairs or previous surgeries to the lower limb were excluded from the study. Controls were included in the study if they were currently engaged in multidirectional field-based sports, had no lower limb injury in the last three months and had no history of lower limb surgery. Participants were also excluded if they did not want to wear a blindfold during the

stepdown balance task. All participants provided informed written consent prior to participation in the study.

Protocol

Participants were tested in a biomechanics laboratory utilising integrated force plates (two force plates each 40x60 centimetres, 1000Hz BP400600, AMTI, USA) during the stepdown test to measure time to stability and identify visual reliance. Following the stepdown test, participants completed a joint position sense task to assess proprioception, and four patient reported outcome measures (PROMs) to determine their level of self-reported knee function, kinesiophobia, fear of reinjury and fear of the stepdown test. This data was collected to determine if there were any correlations between visual reliance and the four PROMs.

Stepdown test

A stepdown task on to a single-leg, assessing time to stability after stepping off a 20cm step, is reliable with full vision in an ACLR population (Colby et al., 1999), and is reliable when completed with full vision and whilst blinded to derive a visual reliance index score in healthy individuals (Chapter 3). Participants were barefoot. A 20cm step was placed behind dual force plates. Participants placed their hands on their hip and stepped off the step with a single leg and upon landing on the force plate, attempted to achieve stability as quickly as they could for 20 seconds. The single-leg landing posture was not standardised for trials; participants were allowed to adopt a strategy that suited them. Participants were asked to keep their head up and their eyes looking forwards. Three successful trials were completed for each leg (ACLR cohort: ACLR limb and uninjured limb. Controls: dominant [DM] and non-dominant [NDM]) in each condition (full vision and blinded vision), with two warmup trials provided for each leg. A maximum of six trials were needed to achieve the three successful trials, which avoided fatigue becoming a limiting factor. For the blinded vision trials, participants were blindfold.

Trials were deemed invalid if the participants removed their hands from their waist, placed their non-testing leg on the ground, shuffled the testing foot on the force plate after landing or removed their blindfold during a trial. Participants removed their blindfold to step back up on the box. Similar to the methodology in Chapter 3, the order of the trials (full vision and blinded vision) was not randomised which may potentially result in improved performance due to practice or order effect. However, to minimise this, when completing trials within a particular visual condition, the participants were provided with warm up trials and then trials would alternate between legs.

Joint position sense test

Proprioceptive deficits are common following an ACLR due to the loss of proprioceptors within the native ACL (Relph and Herrington, 2016b). Following an ACLR, the ACL graft is reinnervated. Although, there are varying rates of reinnervation, proprioceptive deficits are commonly resolved by six months post-surgery (Hoshiba et al., 2020; Ordahan et al., 2015). A joint position sense (JPS) test was completed to determine if proprioceptive deficits were evident in the participants of this study. Proprioceptive deficits amongst the participants would limit the conclusions that could be drawn on the occurrence of visual reliance as it would be a confounding factor to performance on the stepdown test.

JPS testing was utilising VICON 3D (Nexus version 2.12) assessment and an eight-camera motion analysis system (200Hz: Bonita-B10, Vicon, UK) recording 24 reflective markers (1.4cm diameter). This procedure has been previously detailed (King et al., 2018). Participants were barefoot with reflective markers secured to the skin using double-sided tape, at bony landmarks on the lower limbs, pelvis and trunk according to the plug-in-gait marker set (Marshall et al., 2014). Motion data were low-pass filtered using a fourth-order Butterworth filter (cut-off frequency of 15Hz) (Kristianslund et al., 2012).

The JPS testing protocol was adapted from Relph and colleagues (Relph and Herrington, 2016b; Relph and Herrington, 2015b) which has been shown to be reliable in uninjured controls (Relph and Herrington, 2015b). Internal reliability testing of this adapted JPS testing protocol resulted in intraclass coefficient values of 0.76-0.86 and standard error of measurement values of 0.88-1.23° and minimal detectable change values of 2.44-3.40° (Appendix A). Participants were seated on a chair with their back unsupported and knees off the edge of the chair. The lateral femoral condyle was 10cm anterior to the edge of the chair to ensure that the skin around the knee, especially in the popliteal fossa, did not touch the chair and thereby provide any extra mechanosensitive information to the patient. The participant's relaxed leg was passively extended by the examiner to an angle between 0° and 45°. The participant was instructed to actively hold this angle for five seconds and to "make a mental note of how their knee is positioned and to remember the feeling of this target angle" whilst the examiner removed their support of the leg. The examiner then brought the participant's knee back to the starting position. Participants were then instructed to actively extend their knee to the position of the target angle and hold it there for five seconds. A total of five trials were collected for each leg.

Absolute error was recorded for each trial, which is the angular difference between the target angle set by the examiner and the angle replicated by the participant.

PROMs

Self-reported knee function was assessed using the International Knee Documentation Committee (IKDC) Subjective Knee Form (Higgins et al., 2007). The IKDC is scored out of 100 points whereby a higher score denotes better self-reported knee function. ACLR participants' knee confidence and psychological readiness for return to sport were assessed using the ACL Return to Sport After Injury (ACL-RSI) scale (Webster and Feller, 2021; Kim et al., 2022). The scale is reported as a score between zero and 100, whereby a higher score denotes greater confidence and psychological readiness for a return to sport. To assess kinesiophobia, which could

theoretically affect performance during the stepdown test, the 17-point Tampa Scale of Kinesiophobia (TSK-17) was utilised (Dupuis et al., 2023). The scale is results in a score between 17 and 68, in which 17 denotes no kinesiophobia whilst 68 indicates extreme kinesiophobia.

Finally, prior to completing the stepdown test with their eyes closed, participants were asked to rate their fear of completing the task utilising a numerical rating scale between zero and ten, whereby zero indicated no fear of the task and ten indicated they were extremely fearful.

All of the PROMs utilised are valid and reliable measures to assess self-reported knee function (Higgins et al., 2007), knee confidence and psychological readiness for return to sport (Webster et al., 2008), kinesiophobia (Dupuis et al., 2023; Swinkels-Meewisse et al., 2003) and fear of the task (Karvounides et al., 2016).

Data processing

Data processing for the stepdown and JPS tests were conducted with customised programs in MATLAB (Version R2015a; MathWorks). For the stepdown test, sequential estimation was used to determine time to stability (TTS) (Colby et al., 1999). To undertake sequential estimation, a cumulative average trace was calculated on vertical, anterior-posterior (AP) and medial-lateral (ML) force traces separately and utilised a threshold time of 10 seconds. Upper and lower bounds were calculated for all directional forces; upper and lower bounds were defined as the mean (μ) of the force trace plus and minus the standard deviation (σ) multiplied by 0.25, respectively.

$$upper\ bound = \mu + 0.25\sigma$$

$$lower\ bound = \mu - 0.25\sigma$$

Ground contact was determined as the point in which the vertical ground reaction force surpassed 20N. The TTS was then determined as the last point at which the cumulative trace crossed either the upper or lower bounds and remained within the bounds.

TTS measures were taken for each trial in both the AP and ML directions The resultant TTS was calculated utilising the combined AP and ML values (Webster and Gribble, 2010):

$$Resultant\ TTS = \sqrt{APTTS^2 + MLTTS^2}\ .$$

The visual reliance (VR) index was then calculated using the TTS measures in each direction (ML, AP and resultant):

$$VR\ index = \left(\frac{[TTS\ (blinded) - TTS\ (full\ vision)]}{TTS\ (full\ vision)}\right)\ x\ 100$$

A positive VR index value indicates greater visual reliance.

For the JPS test, the absolute error (AE) was recorded for each trial, which is the angular difference between the target angle set by the examiner and the angle replicated by the participant. The mean of the AE across five trials was calculated for each participants' legs.

Statistical analysis

Data were analysed using SPSS version 28.0 (SPSS, Chicago; IL). Statistical means and standard deviations for all measured variables were calculated for the ACLR and control groups. A mixed analysis of variance was conducted to assess the impact of limb (within factor: injured and uninjured for ACLRs and dominant and non-dominant for controls) and group (between factor: ACLR and controls) on VR index scores (ML, AP and resultant) and JPS. All variables were continuous measures. Previous research has demonstrated no significant difference in balance performance between dominant and non-dominant limbs in healthy controls (Stoddard et al., 2022; Dębski et al., 2017), so therefore to compare the ACLR and control groups, the ACLR limb was matched to the control group's dominant limb (the participants' dominant kicking leg) whilst the uninjured limb of the ACLR group was matched to the non-dominant limb of the control group. Significance was set at $p<0.05$ and effect sizes were calculated with partial η^2, using small (0.01), medium (0.06) and large (0.14) classifications (Richardson, 2011). Independent *t*-tests were

utilised to compare differences between ACLR and control group with regards to their PROMs results (IKDC, ACL-RSI, TSK-17 and fear of stepdown). Significance was set at $p<0.05$ and effect sizes were calculated with Cohen *d*, using small (<0.5), medium (0.5-0.8) and large (>0.8) classifications (Sullivan and Feinn, 2012).

To determine if there was a relationship between the VR index scores and patient reported outcome measures (PROMs), Pearson correlation was utilised with significance set at $p<0.05$ and rho (r) measuring the strength of the correlation, using weak (0.10-0.39), moderate (0.40-0.69), strong (0.70-0.89) and very strong (0.90-1.00) classifications (Schober et al., 2018).

4.4 Results

No statistical differences were evident between the ACLR and control groups with regards to age, height, body mass and activity level (Tegner score) (Table 4.4.A). The stepdown test and JPS results for each group are presented in Table 4.4.B.

Table 4.4.A. Participant demographics. Mean values presented with standard deviation in paratheses.

	ACLR	Controls	Significance (p value)
Number	47	45	
Age (years)	24.1 (4.2)	24.4 (4)	0.68
Height (cm)	180.2 (5.8)	181.6 (7.7)	0.31
Mass (kg)	82.6 (11.1)	82.6 (9.4)	0.99
Tegner score	7.4	7.6	0.53
Time post-surgery (months)	8.8 (1.3)		

Abbreviations: cm= centimetres, kg= kilograms

VR index score- ML

There was a significant moderate interaction between limb and group on VR index score in the ML direction, Wilks' Lambda= 0.93 ($F(1,90)=6.86$, $p=0.01$, partial $\eta^2=0.071$) (Table 2). Simple main effects analysis indicated there was a significant moderate difference in VR index score between the ACLR injured limb and the control dominant limb ($F(1,90)= 8.36$, $p=0.005$, partial $\eta^2=0.085$), with the ACLR injured limb VR index score being positive and larger (greater visual reliance). However, there was no significant difference between the ACLR uninjured limb and the control non-dominant limb ($F(1,90)= 0.50$, $p=0.482$, partial $\eta^2=0.006$).

There was a large significant effect of limb on VR index score within the ACLR group ($F(1,46)= 9.17$, $p=0.004$, partial $\eta^2=0.166$), with significantly greater visual reliance for the injured limb than the uninjured limb. There was no significant difference between limbs in the control group ($F(1,44)= 0.23$, $p=0.632$).

Table 4.4.B. Results of VR index and JPS for ACLR and control groups.

		ACLR		**Controls**	
		ACLR limb	Uninjured limb	Dominant limb	Non-dominant limb
Stepdown test	VR (ML)	9.60 ± 16.46*§	-4.44 ± 25.66§	-2.73 ± 23.92*	-0.86 ± 22.88
	VR (AP)	4.53 ± 8.09	3.55 ± 7.57	4.44 ± 8.02	3.46 ± 6.32
	VR (resultant)	7.27 ± 10.54*§	0.59 ± 13.53§	1.71 ± 12.17*	2.18 ± 11.88
JPS	Absolute error (°)	2.55 ± 1.32	2.54 ± 1.28	2.50 ± 1.20	2.88 ± 1.33

Abbreviations: ACLR= anterior cruciate ligament reconstruction, JPS= joint position sense, VR= visual reliance index score, ML= medial-lateral, AP=anterior-posterior, *= significant difference between ACLR injured limb and control group dominant limb ($p<0.05$), §= significant different between ACLR limb and ACLR uninjured limb ($p<0.05$)

VR index score- AP

There was no significant interaction between limb and group on VR index score in the AP direction, Wilks' Lambda= 1.00, F(1,90)= 0.00, p=0.999, partial η^2=0.000. There was no significant main effect for limb [F(1, 90)= 0.794, p=0.38] or group [F(1,90)=0.006 p=0.94].

VR index score- Resultant

The same pattern of findings was evident for the resultant as for the ML measure. There was a significant small interaction between limb and group on VR index score in the resultant direction, Wilks' Lambda= .95, F(1,90)= 4.66 p=0.34, partial η^2=0.049. Simple main effects indicated there was a significant small difference in VR index score between the ACLR injured limb and the control dominant limb (F(1,90)= 5.50, p=0.021, partial η^2=0.058), with the ACLR injured limb VR index score being positive and larger (greater visual reliance). However, there was no significant difference between the ACLR uninjured limb and the control non-dominant limb (F(1,90)= 0.36, p=0.552, partial η^2=0.004).

There was a moderate significant effect of limb on VR index score within the ACLR group, (F(1,46)= 7.13, p=0.010, partial η^2=0.134), with significantly greater visual reliance for the injured limb than the uninjured limb. There was no significant difference between limbs in the control group (F(1,44)= 0.05, p=0.830).

JPS

There was no significant interaction between limb and group on JPS, Wilks' Lambda= 0.99, F(1,90)= 1.31, p=0.26, partial η^2=0.014 (Table 4.4.B). There was also no significant main effect for limb [F(1, 90)= 1.12, p=0.29] or group [F(1,90)=0.57, p=0.45].

PROMs

The PROMs results for each group are presented in Table 4.4.C. The ACLR group scored significantly lower on IKDC (t= -13.02, large effect size p<0.001) and ACL-RSI questionnaires (t= -10.24, large effect size, p<0.001) than the control group, indicating lower self-reported knee function and higher risk of reinjury, respectively. The ACLR group scored significantly higher in the TSK-17 questionnaire (t= 3.40, large effect size, p=0.001) than the control group, indicating higher levels of kinesiophobia. In contrast, there was no significant difference between groups with regards to their fear of completing the stepdown test, with both groups rating their fear as very low.

Table 4.4.C. Results of patient reported outcomes measures (PROMs) between ACLR and control groups.

PROMs	**ACLR**	**Controls**	**Cohen's *d***	**p value**
IKDC (0-100)	83.0 ± 8.4	99.4 ± 1.7	-2.67*	<0.001
ACL-RSI (0-100)	67.2 ± 14.1	93.5 ± 10.2	-2.12*	<0.001
TSK-17 (17-68)	31.2 ± 5.2	27.7 ± 4.8	0.71*	0.001
Fear of stepdown (0-10)	1.0 ± 1.7	0.7 ± 1.2	0.22	0.296

Abbreviations: ACLR= anterior cruciate ligament reconstruction, PROMs= patient reported outcome measures, IKDC= international knee documentation committee, ACL-RSI= anterior cruciate ligament return to sport after injury scale, TSK-17= 17 point tampa scale of kinesiophobia, *= significant difference (p<0.05)

Correlations

The relationships between the various PROMs (IKDC, TSK-17, ACL-RSI and fear of stepdown) and VR index score in the two directions that demonstrated significant differences between groups (ML and resultant) were investigated in the ACLR cohort using the Pearson coefficient correlation. There were no significant correlations between the PROMs and VR index scores in the ML and resultant directions for either limb (Table 4.4.D).

Table 4.4.D. Pearson correlations coefficient (r) values between PROMs and VR index score in ML and resultant directions within the ACLR cohort. All results were not significant p>0.05.

		IKDC	TSK-17	ACL-RSI	Fear of stepdown
ACLR limb	ML	0.26	0.04	0.08	0.13
	Resultant	0.24	0.03	0.03	0.21
Uninjured limb	ML	0.21	0.11	0.11	0.19
	Resultant	0.21	0.15	0.22	0.14

Abbreviations: ML= medial lateral, ACLR= anterior cruciate ligament reconstruction, IKDC= international knee documentation committee, ACL-RSI= anterior cruciate ligament return to sport after injury scale, TSK-17= 17 point tampa scale of kinesiophobia.

4.5 Discussion

The results demonstrate that at eight-months post-surgery, ACLR athletes are more visually reliant when completing a stepdown task with their ACLR limb compared to both: (1) the control group, and (2) the uninjured limb within the ACLR group. The difference was noted in both the ML and resultant direction when comparing the ACLR limb to control limb and uninjured limb, with the magnitude of difference being greater than the standard error of measurement previously reported in the Chapter 3 (table 3.4.C) Previous research which also identified visual reliance in ACLR cohorts have utilised measures of cortical activity, which is not clinically

accessible (functional brain MRI and EEG) (Chaput et al., 2021a; Grooms et al., 2017; Criss et al., 2020), but this present study highlights that the stepdown test is able to distinguish between the ACLR limb and uninjured/control limbs which may be related to visual reliance. Our study also demonstrates that visual reliance appears to affect only the ACLR limb.

Visual reliance has been suggested to develop as a compensatory mechanism due to altered somatosensory information following an ACL injury and subsequent ACLR (Grooms et al., 2015a; Grooms et al., 2017; Dauty et al., 2010). Although the injury is unilateral, there has been mixed opinions on whether the visual reliance is unilateral or bilateral. In a cohort of chronic ankle instability patients, visual reliance was bilateral, as determined via a single-leg balance task (Kim, 2020a). Similarly, functional brain MRI in the ACLR population demonstrated altered activation in bilateral sensory pathways following an unilateral injury (Grooms et al., 2017). However, the findings of the present study suggests that visual reliance affects the ACLR limb only. This is supported by Lehmann and colleagues (Lehmann et al., 2021a) who demonstrated significantly greater cortical connection and activation (via EEG measures) during a single-leg balance task on the ACLR limb as compared to the uninjured limb. A suggested theory for unilateral only changes could be due to changes in functional connection between motor planning centres in the brain, which may be a compensatory mechanism for the alteration in somatosensory and spatial information from the knee (Grooms et al., 2017; Lehmann et al., 2021a) and also the inhibition of the limb's efferent system (Criss et al., 2020; Neto et al., 2019a). With ACLR reinjury rates being as high as 9-29% (Rodriguez-Merchan and Valentino, 2022) in some cohorts and reinjury increasingly being framed as the result of errors in motor planning (Piskin et al., 2022), visual reliance affecting motor planning of the ACLR limb may play a role in ACLR reinjury. Future prospective research is required to determine if visual reliance in the ACLR limb leads to increased rates of reinjury or increased measures of risk of reinjury, and whether effective interventions can be used to address these. Also, future research should examine if there is a direct relationship between visual

reliance as determined by the single-leg stepdown task and cortical activity (via functional brain MRI and/or EEG).

The results of the study demonstrate that there was a significant difference in the VM index score in the ML direction whilst no difference was seen in the AP direction. The resultant direction was a combination of both the ML and AP directions, hence why the magnitude of difference between the ACLR limb and uninjured/control limbs reduced. The AP direction may have demonstrated no difference between groups and limbs as it has been suggested that motor control and step self-stabilising in the AP direction requires less sensory feedback such as vision than the ML direction (O'Connor and Kuo, 2009). Greater differences in postural control may therefore be seen in the ML direction as supported by our results. Hence, when using the stepdown test to identify individuals who are visually reliant, clinicians should focus predominantly on the ML direction.

Proprioception is the ability for an individual to sense the movement and position of their body (Taylor, 2009). The ACL is richly innervated with proprioceptors and provides proprioceptive information to the central cortex in aid of motor planning (Park et al., 2005; Strong et al., 2022). Following an ACL injury and subsequent ACLR, there is a loss in proprioceptive information from the ACL to motor planning centres (Fremerey et al., 2001; Jurevičienė et al., 2012). To compensate for this in the early stages, the motor planning centres are reweighted to rely more on visual information (Baumeister et al., 2008; Baumeister et al., 2011; Grooms et al., 2017). Proprioception steadily improves in ACLR cohorts as the graft site is reinnervated and by four to seven months, proprioceptive function in most cases improves to a level no different to uninjured controls (Hoshiba et al., 2020; Furlanetto et al., 2016; Moezy et al., 2008). However, although proprioception improves over time, it appears that visual reliance may remain as ACLR cohorts, even 2 years post-surgery, demonstrate visual reliance on functional brain MRI (Chaput et al., 2021a; Criss et al., 2020; Grooms et al., 2017). It has been suggested that visual reliance may result in poorer motor control when visual information is absent (Grooms et al., 2015a). However,

a potential confounder in determining if an individual has visual reliance is if the individual's proprioceptive ability is reduced. In the present study, the ACLR cohort had no difference in proprioceptive ability, as measured by the joint position sense testing, in comparison to the control group. Therefore, it suggests that the reduction in motor control in the ACLR limb when vision was blinded was due to a reweighting to being more visually reliant, rather than any dysfunction in proprioception.

Fear of movement (kinesiophobia) and reinjury are common following an ACLR and is a significant reason why many athletes do not return to sport (Ross et al., 2017; Burland et al., 2018; Little et al., 2023). Kinesiophobia and fear of reinjury have been previously demonstrated in both ACLR cohorts (Markström et al., 2022) and other clinical populations (Shallan et al., 2023; Alshahrani and Reddy, 2024; Han et al., 2024) to have negative effect on dynamic balance measures. This contrasts with the findings of this study which demonstrated no relationship between the visual reliance index scores and (i) kinesiophobia (TSK-17), (ii) fear of reinjury (ACL-RSI), (iii) self-reported knee function (IKDC) or (iv) fear of the stepdown task. A potential reason for the difference in findings may be due to the nature of the task used to assess balance. The task used by Markström and colleagues (2022) was a lateral rebound jump which may heighten an athlete's fear when performing the task following an ACLR due to the plyometric nature of the task and the greater demands on controlling body segments in the frontal plane, which may lead to higher loads through the ACL (Bates et al., 2015; Bates et al., 2019; Kiapour et al., 2016; Kiapour et al., 2014). In contrast, the stepdown test used in the present study is a simpler task that athletes complete regularly in their normal daily activities and may therefore be less likely to create fear. This may have implications on future research assessing visual reliance via a landing task, as it supports using tasks that do not raise fears through excessive loading.

The clinical relevance of the study is that it supports the suggestion that following an ACLR, athletes can become visually reliant when planning motor tasks for the ACLR limb. It also

highlights, that the stepdown test can be safely conducted in ACLR individuals in a clinical setting to assess whether athletes are visually reliant. This has implications for both rehabilitation and return to sport testing. Visual reliance has been suggested as a risk factor for future reinjury (Grooms et al., 2015c) and therefore clinicians should address this with all ACLR patients but they may use the stepdown test to identify individuals who may need more targeted rehabilitation strategies (Gokeler et al., 2019; Grooms et al., 2015a). By regularly measuring an individual's visual reliance via the stepdown test, it will help to identify rehabilitation strategies that are effective in treating visual reliance. Return to sport testing has commonly focused on strength, explosive qualities and movement technique measures. The addition of the stepdown test may help to identify individuals who are potentially at high risk of reinjury when returning to sport.

A limitation of the study was that landing posture was not controlled during the stepdown test. On one-hand this could affect and individual's time to stability measure and hence lead to altered VR index scores, while on the other hand it may inappropriately constrain their natural landing action. Future research should explore this. Future research combining the stepdown test with measurements of central cortical activity (eg. EEG) would be beneficial to identify the unilateral pathways that are responsible for the visual reliance. Finally, future research should explore if visual reliance (and the level of visual reliance) is related to ACLR reinjury and determine strategies to treat/rehabilitate visual reliance.

4.6 Conclusion

ACLR athletes, eight months post-surgery, demonstrated increased visual reliance of the ACLR limb as compared to their uninjured limb and that of healthy controls. The increased visual reliance identified was greater than the standard error of measurement of the stepdown task (in both the ML and resultant directions). The visual reliance of the ACLR limb appears to be independent of the athletes' level of self-reported knee function, fear of reinjury and

kinesiophobia. This may be a contributor to the relatively high rate of reinjury but requires further studies. Rehabilitation strategies should target visual reliance to potentially reduce the risk of reinjury.

When employing the stepdown test, utilising the VM index score in the ML direction appears to be the most appropriate in identifying individuals who are visually reliant.

Relevance of this Chapter's findings to the thesis

The aim of this chapter was to investigate if ACLR athletes eight months post-surgery were more visually reliant than healthy controls. The stepdown task identified that the ACLR limb was more visually reliant than the uninjured limb or healthy control limb. No difference was found in proprioceptive function of the knee between groups which would suggest that ACLR athletes had regained proprioceptive function and therefore the differences noted in the stepdown task could be better ascribed to being visually reliant in the ACLR limb. This subsequently led to the biomechanical analysis in Chapter 7 to determine the effect of visual reliance on unplanned change of direction biomechanics. However, some researchers have suggested that visual processing deficits (eg. visual memory deficits, poor reaction times, poor visual processing speeds and poor tacking abilities) may be related to visual reliance (Chaput et al., 2021a). It is thought that if an individual's visual processing ability is poor, then it may confound tests identifying visual reliance as individuals will need to utilise more visual processing resources for the same task as another individual to avoid making errors. Therefore, assessing visual processing abilities in an ACLR cohort would be an important step to ensure that the visual reliance identified in the eight-month post-surgery ACLR cohort is not confounded by visual processing deficits. However, there is large heterogeneity in assessment tools utilised with mixed findings with some studies utilising concussion software to assess visual processing abilities as part of neurocognitive testing (Chaput et al., 2021a; Bodkin et al., 2021; Stone et al., 2018). Therefore, the utilisation of specific software

systems designed for visual processing abilities may be of greater benefit when assessing for deficits as they assess athletes across a broader range of visual processing abilities. Whilst one such software, Senaptec sensory station (formerly Nike Sparq), has been shown to be reliable when utilised on a television screen, the smaller tablet software system from the same manufacturer has not been examined. The reliability of the tablet system will be examined in Chapter 5.

Chapter 5

Reliability of a tablet system assessing visual processing abilities

5.1 Introduction

Athletes are required to make complex decisions and movements in a chaotic sporting environment. They utilise their sensory information, including vision and visual processing abilities, to perceive the sporting environment to then assist motor planning centres to generate an appropriate movement (Gibson, 1986). Therefore, errors in decision making due to poor vision or visual processing ability could lead to injurious movement strategies being employed. There is an increasing trend to frame non-contact lower limb injuries such as anterior cruciate ligament (ACL) injuries as neurophysiological injuries, in that they are the result if an error in motor planning and execution (Swanik, 2015; Stańczak et al., 2025).

A method of testing an athlete's ability to process sensory information is neurocognitive testing as it contains tasks which assess various visual skills such as visual memory, visual processing speed and reaction time (Iverson et al., 2003). Neurocognitive testing utilising software primarily designed for concussion assessment has demonstrated that athletes with worse visual memory, slower reaction times and slower visual processing speeds were more likely to sustain a future ACL injury(Swanik et al., 2007). Visual memory and visual motor subscales on the same neurocognitive software was shown to be associated with increased neural activity in visual-motor cortical regions within ACL reconstructed (ACLR) athletes but not within an uninjured control group (Chaput et al., 2021a). However, a criticism of concussion related neurocognitive software is that they do not assess visual processing across a broad spectrum and focus merely on a handful of abilities.

Software systems to assess a broader range of visual processing abilities have been developed for television and tablet screens. These systems, commonly termed 'sensory stations', have been produced by Nike (Sparq system) and subsequently extended with the Senaptec system (Senaptec USA). The sensory stations test visual processing across a number of abilities, including visual clarity, depth perception, multiple objection tracking and reaction times (Wang et al., 2015). It has been suggested that they may be more ecologically valid than computer based neurocognitive testing when examining visual processing abilities in athletes(Grooms et al., 2015a). The Nike Sparq system has been previously been shown to be reliable across a number of visual processing tests (Erickson et al., 2011) and has been utilised to understand visual processing abilities in athletes (Burris et al., 2020). The Senaptec sensory station, however, utilises both a television screen and a tablet system. While the tablet system allows for increased portability for clinicians to carry out testing, no reliability assessment has been published for the system to date.

The aim of this study was to determine the test-retest reliability of the Senaptec sensory tablet system for assessing seven visual processing abilities.

5.2 Methods

Participants

A repeated measures design was utilised with participants tested twice, five to seven days following their first testing session. Fifteen healthy participants (5 females, 10 males, age= 25.6 ± 4.6 years, height= 178.6 ± 10.5cm & mass= 78.6 ± 13.1kg) (see Table 5.2) took part in the study. Participants were currently involved in competitive pivoting sports (average Tegner scale score= 6.8). Participants were excluded if they had any musculoskeletal, brain, neurological or eye injuries within the last 12 months. Informed consent was obtained from all participants and was approved by the ethics and research committee of the Sports Surgery Clinic, Dublin, Ireland. A priori power analysis was conducted utilising 'Sample size calculator (web)' (Arifin, 2025). 11 participants were required when an expected ICC value of 0.9, minimum acceptable ICC value of 0.5, significance level of 0.05 and power at 80% were required.

Table 5.2. Participant Demographics. Mean Values Presented with Standard Deviation (SD)

	Male (SD)	Female (SD)	Total (SD)
Number of participants	10	5	15
Age (years)	26.2 (4.8)	23.8 (3.4)	25.6 (4.6)
Height (cm)	184.6 (6.7)	166.6 (4.0)	178.6 (10.5)
mass (kg)	86.3 (8.2)	63.4 (3.2)	78.6 (13.1)
Tegner score	7.0	6.4	6.8

Abbreviations: cm= centimetres, kg= kilograms

Procedure

A tablet system (13.3-inch screen, 1920 x 1080 resolution) (Senaptec, USA) loaded with seven testing modules was fixed to a tripod. The height of the tripod was adjusted such that the centre of the tablet was at eye-level of the participants. All participants were given the same explanation and verbal cues. Prior to each of the seven testing modules, participants were given a brief explanation and short practice trial. The tests were completed in the following order: visual clarity, contrast sensitivity, depth perception, near-far quickness, perception span, multiple objects tracking and reaction time. The order of the tests were set by the manufacturer as the first three tests (visual clarity, contrast sensitivity and depth perception) influenced how the system set up the imagery used in the near-far quickness test. Perception span and reaction time testing was pertinent given previous work which has demonstrated that those who sustained an ACL injury had worse visual memory and slower reaction times than matched athletes (Swanik et al., 2007). Near-far quickness and multiple object tracking was completed in the study as previous studies have related these visual processing abilities to how well athletes can execute certain sporting skills (Poltavski and Biberdorf, 2015; Guo et al., 2024; Burris et al., 2020) All tests were conducted at UPMC SSC Sports Medicine (Dublin, Ireland) and on both occasions, the same room, equipment and investigator were used for all test subjects.

Participants stood three metres away from the tablet for the visual clarity, contrast sensitivity, depth perception and near-far quickness tasks and at arm's length away from the tablet for the perception span, multiple object tracking and reaction time tasks. They utilised a mobile phone, provided with the tablet system, that was paired to the tablet to allow participants to input responses when standing 3m from the tablet. They input their response directly onto the tablet when standing at arm's length from it.

Visual clarity assesses the static visual acuity of participants with both monocular (single eye) and binocular vision. Visual performance tests are influenced by an individual's visual acuity and hence this test was conducted first. During the test, a handheld eye occluder was used to block the vision of an eye during the monocular vision aspect of the test. The right eye was tested first, followed by the left, and finally both eyes together. Participants were presented with a circle that was missing an edge (Figure 5.2A). The participants were tasked with swiping their finger in the direction of the opening and in the case of Figure 5.2A, the participant would need their finger up on the mobile device. The software would then change the size of this circle and the side of the opening to accurately score the participants' visual acuity. The results obtained were a logarithmic of the minimum angle of resolution scores and converted to a fraction score of 20 feet as this is what is commonly encountered in the community (eg. 20/20 and 18/20 vision). A score of 20/20 vision demonstrates good vision. A score of 18/20 indicates poorer vision as the participant needs to stand at 18 feet to see an object that the average individual could see at 20 feet. Similarly, 22/20 vision indicates better vision as the participant can see an object from 22 feet that an average individual would need to stand at 20 feet.

Contrast sensitivity was assessed at 6 cycles per degree (cpd), then 18 cpd. It required participants to identify one of the four circles on the screen that were a different contrast. The participants would then swipe on the screen in the direction (up, down, left or right) of the aberrant circle. Speed of response was of value for this test so participants were encouraged to

take their time and identify the aberrant circle. Following an answer (correct or incorrect), the software would then present a different set of circles at a different contrast setting until a stable measurement of the participant's contrast sensitivity was identified. The resulting score ranged from 0 to 2.2. A higher score indicates better contrast sensitivity performance. A score of 2.0 indicates normal performance and a lower score indicates visual impairment.

For **depth perception**, the participant wore goggles with one red and one cyan lens. They began the test by looking straight ahead and were asked to identify which of the four circles was mis-shaped. The system would then change which circle was aberrant and the size of the circles. This was then repeated whilst participants had their head turned to the left and then to the right. The scores obtained ranged from 0 to 240, with lower scores indicating better performance.

For **near-far quickness**, the participant held the paired mobile phone out in front of their face (at eye level) using their non-dominant arm and swiped the answer on their phone using the pad of the index finger of their dominant hand. Participants had 30s to obtain as many correct answers as possible. The task involved them answering a visual-based problem from the tablet system (Figure 5.2A with object centrally indicating the visual problem and the blue arrow describes the indicated direction that the participant was required to swipe on the screen). A correct answer would result in a new visual problem appearing on the mobile phone device. This quick switching between the two screens occurred over 30s. The results obtained were: (i) the number of correct answers given in 30s, (ii) the average time it took the participant to switch from near to far in milliseconds (average time between correctly answering problem on mobile phone and correctly answering problem on tablet system), and (iii) the average time it took to switch from far to near in milliseconds (average time between correctly answering problem on mobile phone and correctly answering problem on tablet system).

Perception span assessed visual memory. The task required participants to look at a pattern of unfilled circles. Some of the circles then were filled for one second and disappeared. The

participants were then required to input the circles they believed had been filled in (Figure 5.2B). If participants answered correctly, the number of circles on the screen expanded as well as the amount of circles that were filled. The result obtained was the sum of all the circles correctly identified throughout the test.

The **multiple object tracking** test required participants to track clusters of circles (groups of three circles) (Figure 5.2C and D). The target circle was highlighted for two seconds in a different colour. This colour then reverted to the same colour as the other grouped circles. The circles then spun around and when it came to a stop, the participant was tasked with identifying the target circle. Correct answers resulted in the software adding more groupings of circles to track and increasing the speed of rotation. The results obtained from the multiple objects tracking task was an overall score that was a product of the maximum speed of object pair rotation and the maximum number of object pairs tested. A higher score in all three measures indicates better performance.

For the **reaction time** test, participants placed their index fingers on the screen within two circles. When one of the circles became red, participants removed that index finger as quickly as they could. The test was completed when three measures had been correctly recorded for each hand. The results were reported as the reaction time score for the participant's dominant hand, non-dominant hand and an average reaction time across both hands. All reaction time results were in milliseconds which a lower value indicating better performance.

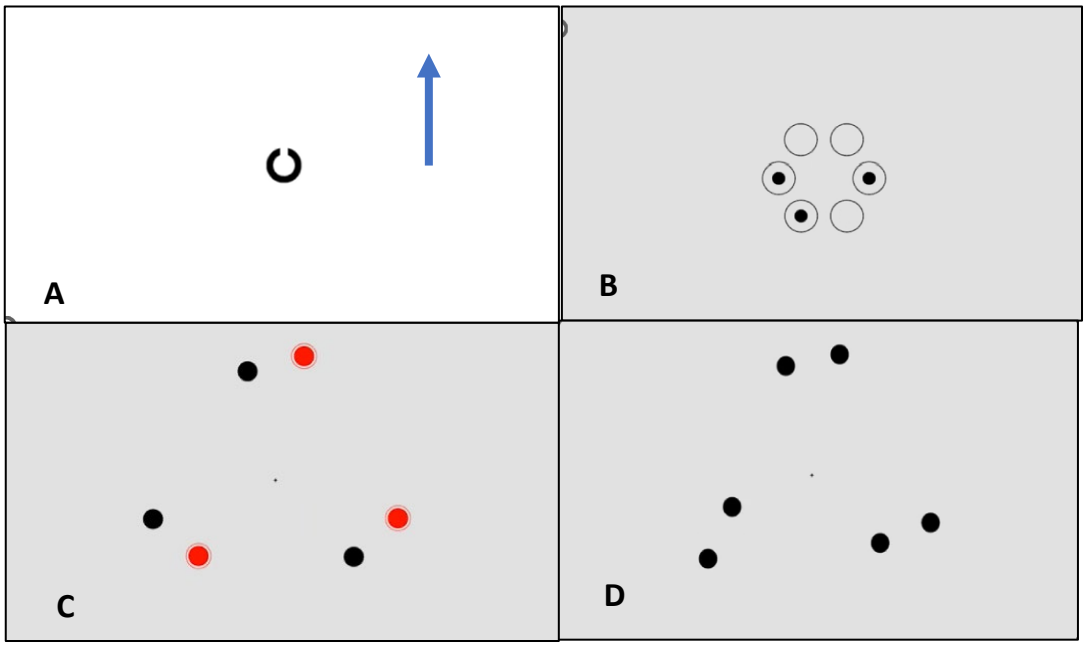


Figure 5.2. Demonstrates the visual tasks encountered on the visual tablet system. **A** indicates the visual problem seen on the screen and the blue arrow represents the direction of the required finger swipe from the participant. **B** demonstrates the filled in circle during the 'perception span' test that participants are to memorise. **C** The red circles are the objects the participant is required to track. **D** The circles are now returned to a normal colour and will spin. When it stops spinning, the participant is to identify which were the previously highlighted circles.

Statistical analysis

Reliability was assessed using two-way random effects model of intraclass correlation coefficient (ICC2,1). 95% confidence intervals (CIs) were calculated for each ICC. ICCs were classified as follows: less than 0.50 as poor, 0.50-0.75 as moderate, 0.75-0.90 as good, and greater than 0.90 as excellent (Koo and Li, 2016). Standard error of the mean (SEM) was calculated as:

$$SEM = Standard\ deviation_{pooled}\ x\ \sqrt{(1 - ICC}$$

Minimal detectable change (MDC) was calculated to allow clinicians to identify when a change is clinically different between two measurements. MDC was calculated as:

$$MDC = SEMx\ 1.96\ x\ \sqrt{2}$$

5.3 Results

All participants completed the visual tasks, and the results, ICC values, SEM and MDC are presented in table 5.3. Overall, the reliabilities of the visual processing tasks were mixed. With regards to visual clarity, the right eye demonstrated good reliability (ICC 0.83, p<0.001) whilst the left eye (ICC= 0.45, p=0.047) and both eyes demonstrated poor reliability (ICC 0.43, p=0.057). Contrast sensitivity also demonstrated mixed reliability with 6cpd being excellent (ICC 0.92, p<0.001) and 18cpd being poor (ICC -0.24, p=0.795). Depth perception demonstrated moderate reliability for the right (ICC 0.69, p=0.002) and the left (ICC 0.58, p=0.01), but poor reliability when utilising both eyes (ICC 0.28, p=0.082).

Near far quickness demonstrated moderate reliability (ICC 0.50, p=0.023) for reaction time to far targets but poor reliability for reaction time to near targets (ICC 0.44, p=0.036) and the overall score (ICC 0.31, p=0.127). Perception span score (ICC 0.67, p=0.003) and multiple object tracking score (ICC 0.60, p=0.009) both demonstrated moderate reliability. Reaction time measures demonstrated moderate reliability for the dominant hand (ICC 0.57, P=0.012) and good reliability for the non-dominant hand (ICC 0.80, p<0.001) and average reaction time for both hands (ICC 0.81, p<0.001).

Table 5.3. Visual processing values, intraclass coefficient (ICC), standard error of measurement (SEM) and minimal detectable change (MDC) values for each of the visual processing tasks

Outcome measure	Mean on Day 1 (SD)	Mean on Day 2 (SD)	ICCs (CI 95%)	p value	SEM	MDC
Visual clarity right eye *(logMAR)*	0.0076 (0.19)	0.0045 (0.25)	0.83* (0.56-0.94)	<0.001	0.09	0.26
Visual clarity left eye *(logMAR)*	-0.0032 (0.18)	-0.0112 (0.18)	0.45* (-0.08-0.78)	0.047	0.13	0.37
Visual clarity both eyes *(logMAR)*	-0.0675 (0.13)	-0.0805 (0.13)	0.43 (-0.11-0.77)	0.057	0.10	0.27
Contrast sensitivity 6cpd *(logCS)*	2.09 (0.27)	2.09 (0.25)	0.92* (.078-0.97)	<0.001	0.07	0.20
Contrast sensitivity 18cpd *(logCS)*	1.49 (0.45)	1.52 (0.25)	-0.24 (-0.72-0.32)	0.795	0.39	1.09
Depth perception both eyes *(arcsec)*	200 (73.71)	210.5 (63.71)	0.28 (-0.17-0.74)	0.082	53.6	148.4
Depth perception left side *(arcsec)*	208.3 (74.69)	195.9 (73.83)	0.58* (0.12-0.84)	0.001	47.74	132.3
Depth perception right side *(arcsec)*	201.5 (73.98)	195.7 (74.64)	0.69* (0.28-0.88)	0.002	41.1	114.0
Near far quickness score *(unitless)*	20.5 (5.29)	21.7 (5.38)	0.31 (-0.23-0.70)	0.127	4.39	12.2
Near far quickness (reaction time to near target) *(ms)*	1044.4 (219.46)	955.6 (222.93)	0.44* (-0.03-0.76)	0.036	169.0	468.5
Near far quickness (reaction time to far target) *(ms)*	1304.82 (327.77)	1210.56 (296.44)	0.50* (0.02-0.80)	0.023	222.8	617.7
Perception span *(unitless)*	46.40 (11.18)	48.07 (12.38)	0.67* (0.26-0.88)	0.003	6.72	18.6

Multiple object tracking composite score *(unitless)*	1727.62 (658.33)	1774.72 (668.32)	0.60***** (0.13-0.85)	0.009	406.2	1125.9
Reaction time average *(ms)*	319.07 (34.33)	322.27 (32.53)	0.81***** (0.52-0.93)	<0.001	14.7	40.8
Reaction time dominant hand *(ms)*	318.73 (33.43)	322.6 (33.03)	0.57***** (0.10-0.83)	0.012	21.5	59.5
Reaction time nondominant hand *(ms)*	319.53 (37.48)	322.4 (43.41)	0.80***** (0.49-0.93)	<0.001	18.2	50.4

Abbreviations: SD= standard deviation, logMAR= logarithmic of minimum angle of resolution, LogCS= logarithmic contrast sensitivity, arcsec= arcsecond, ms= millisecond and, *= p<0.05

5.4 Discussion

The aim of the study was to determine the reliability of the Senaptec sensory tablet system for assessing seven visual processing abilities. The results of study demonstrate mixed reliability across the seven visual processing abilities. These abilities could be grouped into those related to visual quality (visual clarity, contrast sensitivity and depth perception), and to visual processing related to decision making (near far quickness, perception span, multiple object tracking and reaction time). The results suggest that visual quality assessments have mixed reliability whilst those abilities related to decision making, except near far quickness, have moderate to good reliability.

This is the first reliability study of the Senaptec sensory tablet system. A previous study (Erickson et al., 2011) assessed the reliability of the Nike Sparq sensory station, which utilised similar tasks to the sensory tablet in this study (visual clarity, contrast sensitivity, depth perception, perception span and near far quickness) but on a 42 inch television screen rather than the smaller tablet style used in our study. The results of Erickson and colleagues' study (2011) demonstrated good reliability in assessing visual quality tasks (visual acuity, contrast sensitivity and depth perception),

which contrasts the results of this study. The difference in our results may be related to environmental or device factors (e.g. 22 inch in this study vs 42 inch). By having a smaller screen size, the size of the objects on the screen may have been smaller than what was presented on the 42 inch screen. The smaller screen also means that there is potentially greater background noise from the environment and hence may cause the participants to be distracted from the objects on the screen. Differences in brightness of the screen could also affect a participant's contrast sensitivity or depth perception. Similarly, whilst every effort was made to limit glare from the screen, lighting conditions may affect the glare and hence a participant's ability to clearly view the images on the screen.

Whilst visual clarity in this study demonstrated good reliability for the right eye, it's poor reliability for the left eye and both eyes together, suggest that it is not a reliable task to utilise in future research. Snellen and Bailey eye charts, commonly encountered in optometrist clinics, are valid and reliable methods of examining visual clarity (Lovie-Kitchin, 1988) and therefore may be more suited for use in future research. With regards to contrast sensitivity, measurements at 6cpd demonstrated excellent reliability as compared to poor reliability at 18cpd. Erickson and colleagues (2011) reported a similar difference, albeit of a smaller magnitude, between 6cpd and 18cpd. The difference may potentially be related to the increased physiological demands when working at the harder task of 18cpd, meaning that participants are working close to their threshold, and hence small fluctuations in fatigue, attention or screen resolution may result in large differences between the two testing sessions. Depth perception had moderate reliability when measuring participants' head turned to the right and left, but poor reliability when participants' faced the screen straight on. Again this contrasts previous research (Erickson et al., 2011) and potentially may relate to environmental conditions as previously mentioned.

The four remaining tasks (near far quickness, perception span, multiple object tracking and reaction time) measured visual processing in relation to decision making. The near far quickness

task demonstrated mixed reliability with moderate reliability when measuring reaction time to a far target, whilst poor reliability for reaction time to a near target and the overall score. The mixed reliability could be influenced by the same factors as previously discussed related to screen resolution, screen glare and environmental lighting. Another potential factor for the poor reliability for 'the reaction time to the near target' is that sometimes the input into the manufacturer provided mobile device did not register an answer if the participant did not have adequate fingertip pressure on the screen when swiping. The other 3 outcome measures (perception span, multiple object tracking and reaction time) had moderate to good reliability. This may potentially be because they are the three tests that allowed participants to stand close to the screen (not three metres away from it) and therefore reduces any environmental lighting, glare or screen resolution influences.

A limitation of the study is that the activity of participants 12 hours prior to testing was not controlled. Visual processing abilities can be influenced by a number of factors such as fatigue, caffeine intake and stress (Shackman et al., 2011; Redondo et al., 2021). Whilst, participants were advised to not ingest caffeine 12 hours prior to the study, it was not possible to control fatigue, sleep and stress prior to each testing session and this may therefore provide increased variability to the results.

5.5 Conclusion

The Senaptec sensory tablet system has mixed reliability when assessing visual processing abilities. Contrast sensitivity at 6cpd, depth perception (right and left), perception span, multiple object tracking and reaction time assessments demonstrated moderate-to-good reliability. The tablet system should not be used to assess visual clarity, contrast sensitivity at 18cpd or near far quickness due to its poor reliability.

Link between Chapter 5 and 6

The Senaptec sensory tablet system demonstrated moderate-to-good reliability across several visual processing abilities (such as perception span, multiple object tracking and reaction time). Differences in visual processing abilities has previously been shown to be related to ACL injury (Swanik et al., 2007). It is thought that those with poorer visual processing abilities may respond to visual stimuli on a chaotic sporting field slower and make incorrect decisions, which may lead to injury due to the athlete employing a suboptimal or injurious movement technique. It is important that this is investigated in the ACLR cohort because if a difference is identified, then this assessment tool will need to be added to the study in Chapter 7 to determine if it affects any relationship between visual reliance and unplanned change of direction biomechanics. Therefore, Chapter 6 is to examine if there are any visual processing differences between ACLR and health control cohorts.

Chapter 6

Visual processing abilities do not differ between ACLRs and healthy controls

6.1 Introduction

Anterior cruciate ligament (ACL) injuries predominantly occur with a non-contact mechanism such as change of direction, deceleration and landing tasks (Boden et al., 2000). This suggests that ACL injuries are the result of an error in motor planning and execution.

The visual system is thought to be the predominant sensory system utilised for motor planning tasks (Santello et al., 2001; Sarlegna and Sainburg, 2009). Therefore, dysfunction in the visual system could potentially result in motor planning errors and hence ACL injuries (Swanik, 2015; Grooms et al., 2015c). There are a limited number of studies investigating visual processing abilities in the ACL and ACLR population. There is only one study that prospectively investigated whether visual processing deficits lead to injury (Swanik et al., 2007). It demonstrated that college athletes who sustained an ACL injury had slower reaction times, slower visual processing speed and poorer visual memory as compared to matched athletes who did not injure their ACL. These visual processing abilities were measured via neurocognitive computer-based testing as part of baseline testing. There are no such prospective studies investigating visual processing abilities in the ACLR population and their link to reinjury. Much of the literature in the ACLR cohort investigates visual processing ability at one time point to determine if differences between the ACLR and healthy control cohort exists, to determine indirectly if there is a visual processing ability that was related to their initial ACL injury. A study utilising the same neurocognitive

computer-based testing software as Swanik and colleagues (2007) demonstrated no difference in visual memory between ACLR and healthy controls (Chaput et al., 2021a). Therefore, examining across a number of different visual processing abilities (reaction time to visual stimuli, gaze tracking and object tacking) have been suggested determine if there are differences between ACLR and healthy control cohorts but mixed results have been reported across a small number of studies (Stone et al., 2018; Armitano-Lago et al., 2020; Bodkin et al., 2021). The mixed results are potentially due to the heterogeneity in outcome measures utilised (Vitharana et al., 2024). Sensory stations, such as the system developed by Senaptec (USA), are a new and growing area of technology in which a number of visual processing abilities are measured: multiple object tracking, visual clarity, near far quickness and depth perception. To date, no study has examined a broad spectrum of visual processing abilities following ACLR.

The aim of this study was to determine if visual processing abilities (contrast sensitivity, depth perception, multiple object tracking, perception span and reaction time) differ between ACLR athletes eight months post-surgery and healthy controls.

6.2 Methods

ACLR and control athletes were recruited for this cohort study between November 2021 and February 2025. ACLR athletes were recruited from the list of four surgeons at the UPMC Sports Surgery Clinic, Dublin, Ireland (R.M., C.M., M.J., D.W.), whilst controls were recruited from advertisements in local sporting teams. The study received ethical approval from the Sports Surgery Clinic Ethics Committee (APMOC9102CSSIVHT).

Participants and Setting

Ninety-one male participants aged between 18 and 36 years of age were included in the study. ACLR participants who were included if they were greater than seven months post-surgery, had

returned to training, played a multidirectional field-based sport and intended to return to the same level of sport or higher. All ACLR participants underwent primary ACLR with either a bone-patellar tendon-bone or quadriceps tendon graft. Participants who had concomitant ligament repairs or previous surgeries to the lower limb were excluded from the study. Controls were included in the study if they were currently engaged in multidirectional field-based sports, had no lower limb injury in the last three months and had no history of lower limb surgery. Due to the nature of the visual processing testing, participants were excluded if they had any visual dysfunction, past or current injury to the eye affecting their vision, concussion in the last 6 months or the presence of chronic symptoms following a concussion.

Protocol

Participants were tested within a sports medicine facility utilising a tablet system containing visual sensory assessment software (Senaptec, USA). The tablet (13.3 inch screen) is preloaded with seven tasks but only five were utilised, due to the poor reliability of the other two tasks, for this study: contrast sensitivity, depth perception, perception span, multiple object tracking and reaction time. Details of each test can be found in Chapter 5 and have been demonstrated to be reliable (ICCs 0.57-0.81) (Chapter 5). Prior to each task, participants were explained the task by the examiner and a practice round was provided for familiarisation. A previous reliability study of a similar tablet system demonstrated one familiarisation practice round was appropriate as no learning effect over time was found (Erickson et al., 2011). Upon successfully completing each task, the sensory tablet would progress to the next task.

Data processing and statistical analysis

Following the completion of the five tasks, the results were exported into excel to view the raw scores. The five tasks resulted in eight variables: contrast sensitivity at 6 cycles per degree, depth perception left, depth perception right, perception span, multiple object tracking, reaction time dominant hand, reaction time non-dominant hand and reaction time average. Data were analysed using SPSS version 28.0 (SPSS, Chicago; IL). Statistical means and standard deviations for all

measured variables were calculated for the ACLR and control groups. To determine if a significant difference was present between the ACLR and the control groups, independent t-tests were conducted for all dependent variables (contrast sensitivity at 6 cycles per degree, depth perception [left and right], perception span, multiple object tracking, reaction time [dominant hand and non-dominant hand]). Due to the number of dependent variables examined, a Bonferroni correction was performed (0.05/8) so that a p value of <0.0625 would be required to determine significance. Cohens d effect size was utilised to indicate the magnitude of the difference with <0.2 being a small effect, 0.2 to 0.8 being a medium effect and >0.8 being a large effect. A priori power analysis utilising GPower (version 3.1.9.7) with expected effect size (Cohens d) of 0.6, with a significance of 0.05 and power of 80%, resulted in 45 participants being required in both the ACLR and healthy control groups.

6.3 Results

A total of 91 participants completed the testing procedure and were included in the analysis (ACLR= 46 and controls= 45) which no significant difference in demographics between the groups (Table 6.3.A). Descriptive statistics for each visual processing ability are presented in Table 6.3.B.

Table 6.3.A. Participant Demographics. Mean Values Presented with Standard Deviation (SD)

	ACLR (SD)	**Controls (SD)**	**P value**
Number of participants	46	45	
Age (years)	23.7 (2.7)	24.4 (4)	0.83
Height (cm)	182.7 (7.9)	181.6 (7.7)	0.42
mass (kg)	83.7 (6.1)	82.6 (9.4)	0.98
Time post-surgery	8.7 (1.2)		

Independent *t*-tests revealed no significant differences between ACLR and control groups across all five visual processing abilities (eight variables). Specifically, there were no group differences for contrast sensitivity at 6 cycles per degree, depth perception (left and right sides), perception span, multiple object tracking, or reaction time (average, dominant hand, and non-dominant hand). All *p*-values exceeded the Bonferroni-adjusted threshold for significance. Effect sizes (Cohen's *d*) ranged from trivial to small, indicating negligible group differences.

Table 6.3.B. Descriptive and t-test results between ACLR and control participants across five visual processing tasks

	ACLR		**Controls**		**t-test**	**Significance**	**Effect size**
	mean	SD	mean	SD	df(90)	p value	Cohens d
Contrast sensitivity 6cpd (logCS)	2.08	0.20	2.13	0.17	-1.17	0.24	-0.25
Depth perception Left side (arcsec)	216.1	51.6	221.8	48.2	-0.54	0.59	-0.11
Depth perception right side (arcsec)	204.4	65.1	214.4	56.7	-0.78	0.44	-0.16
Perception span (unitless)	37.5	12.4	39.6	12.2	-0.80	0.42	-0.17
Multiple object tracking (unitless)	1480.8	538.0	1515.4	517.2	-0.31	0.75	-0.07
Reaction time-average (ms)	326.0	34.9	321.6	27.7	0.68	0.50	0.14
Reaction time-dominant hand (ms)	328.7	37.8	322.3	28.1	0.92	0.36	0.19
Reaction time-nondominant hand (ms)	323.2	35.8	321.2	30.9	0.62	0.77	0.60

Abbreviations: SD= standard deviation, df(90)= degrees of freedom, cpd= cycles per degree, logCS= logarithmic contrast sensitivity, arcsec= arcsecond and, ms= millisecond

6.4 Discussion

The aim of the study was to determine if there were any difference in visual processing abilities across five abilities: contrast sensitivity, depth perception, perception span, multiple object tracking and reaction times between ACLR and healthy controls. The results of the study demonstrate no significant difference between the ACLRs and healthy controls for any of the tested visual processing abilities. These findings suggest that either: (i) visual processing ability, as assessed by the Senaptec tablet system, may not be impaired following ACLR in male athletes intending to return to multidirectional sport, or (ii) the Senaptec tablet system is unable to detect differences that are present.

There are a limited number of studies investigating visual processing differences between ACLR individuals and healthy controls. The results of this study align with previous work by Chaput and colleagues (2021), who reported no differences in visual memory scales between ACLR individuals and healthy controls when assessed with computerised neurocognitive testing. This would suggest that assessing visual memory in ACLR participants is not required during rehabilitation and return to play. With regards to reaction times, the results of this study demonstrated no significant difference between the two groups which is supported by Stone and colleagues (2018) who utilised computer-based reaction time testing. However, this is contrasted by Armitano-Lago and colleagues (2020) who showed that ACLR participants had slower reaction times than healthy controls when performing a postural task such as stepping forwards in response to a light stimulus. The discrepancy across studies may be explained by methodological heterogeneity, including the use of different outcome measures and task demands (Vitharana et al., 2024). Future assessments of reaction time in the ACLR population may need to focus on lower limb tasks rather than upper limb tasks.

No previous studies examined the contrast sensitivity and depth perception in ACLR individuals. The results of the present study suggest that basic visual function does not differ between ACLR

individuals and healthy controls. Only one other study (Jiménez-Martínez et al., 2025) has examined the ability of ACLR individuals to track multiple objects, with contrasting results to the present study. Jiménez-Martínez and colleagues (2025) showed that ACLR individuals had poorer ability to track multiple objects as compared to healthy controls. This potentially could be due to differences in the speed that the objects were travelling during the task. The objects in Jiménez-Martínez and colleagues (2025) were travelling at 28.8°/second as compared to 180-240°/second in the present study.

It has previously been shown that college-level athletes who prospectively sustained a primary ACL injury demonstrated worse reaction times and visual memory scores as compared to those who did not (Swanik et al., 2007). The results of the present study and previous studies (Chaput et al., 2021a; Stone et al., 2018), show that following ACLR and rehabilitation, there is no difference between ACLRs and healthy controls. A possible explanation for the lack of group differences may be that athletes recover (improve) their visual processing abilities during the rehabilitation process. There is a growing appreciation amongst rehabilitation staff that rehabilitation following ACLR requires visual-motor (Vitharana et al., 2025b; Grooms et al., 2015a) and visual-cognition exercises (Taberner et al., 2025a; Taberner et al., 2025b). This may result in ACLR individuals improving their visual processing abilities through their rehabilitation program. Another potential explanation for the results is that visual processing deficits, if present, are subtle and may only emerge during more complex, dual-task or sports-specific conditions, rather than isolated tests. This is supported by dual-task tests, such as measuring gaze tracking errors whilst tracking an object and maintaining postural control in single limb stance, which have demonstrated differences between ACLR individuals and healthy controls (Bodkin et al., 2021; Roelofsen et al., 2020).

Limitations of this study include the restriction to male participants limits the generalisability of results to female athletes. Female athletes have a higher risk of ACL injury (Mancino et al., 2023)

and therefore visual processing ability may be relevant in that population group. The cross-sectional design limits the ability to determine if visual processing ability changes over the course of rehabilitation.

6.5 Conclusion

This study demonstrated no difference in visual processing abilities between ACLR individuals and healthy controls. The results suggest that isolated visual processing abilities (contrast sensitivity, depth perception, perception span, multiple object tracking and reaction time) as assessed by the Senaptec tablet system, are not impaired following ACLR when measured at eight months post-surgery. Future research should look to explore visual processing abilities and how they influence decision making under different testing conditions, such as dual-task, visual attention or inhibitory control tasks, to determine if there are differences between ACLRs and healthy controls.

Relevance of this chapter's findings to the thesis

The aim of this chapter was to identify if there were any differences in visual processing abilities between ACLR athletes and healthy controls. No difference was identified between the two groups across several visual processing abilities. It has been suggested previously that visual processing differences may be related to visual reliance. However, the implications of this chapter on the thesis is that visual processing abilities are not related to the visual reliance in the ACLR cohort previously identified in Chapter 4. Therefore, Chapter 7 will examine visual reliance on unplanned change of direction biomechanics without the need to assess for visual processing abilities.

Chapter 7

The effect of visual reliance on unplanned change of direction biomechanics in ACL reconstructed athletes 8 months post-surgery

7.1 Introduction

Anterior cruciate ligament (ACL) injuries occur commonly in multi-directional field-based sports and leads to significant time loss for athletes (six to twelve months) (Martinez-Calderon et al., 2025; Rigg et al., 2023). They predominantly occur during non-contact movements such as change of direction (CoD) or deceleration (Boden et al., 2000), thereby suggesting that an athlete's movement strategy is a significant driver for an ACL injury (Bertelsen et al., 2017). Whilst movement strategy is related to physical capacities, such as neuromuscular strength and power, it is also underpinned by efficient motor planning and execution processes in the brain (Bertelsen et al., 2017; Newell and Liu, 2012). Therefore, inefficiencies in motor planning and execution processes could lead to athletes employing suboptimal and potential injurious movement strategies.

Effective motor planning and execution requires an athlete to efficiently integrate their sensory systems, such as the visual and somatosensory systems. This allows an athlete to adequately appreciate their environment and how their body is positioned within it. A movement strategy can then be executed relevant to the athlete's current task. Errors in the sensory systems or in the integration of the sensory information can lead to suboptimal movement strategies being employed. The ACL is richly innervated with proprioceptors and provides sensory information

within the somatosensory system (Dhillon et al., 2011). Following an ACL injury and subsequent ACL reconstruction (ACLR), there is altered somatosensory information from the knee and a potential shift in the athlete relying more on the visual system for motor planning and execution (Vitharana et al., 2024; Vitharana et al., 2025a; Grooms et al., 2015a). While it has been suggested that athletes who demonstrate more visual reliance (VR) are at greater risk for ACLR reinjury (Grooms et al., 2015c; Vitharana et al., 2025a) no research to date has examined whether VR influences movement strategy.

CoD is a common mechanism of injury for non-contact ACL injuries (Montgomery et al., 2018; Olsen et al., 2004) and is therefore commonly utilised as part of return to sport testing during ACLR rehabilitation. Unplanned CoD tasks have been used extensively for return to play testing to determine an athlete's readiness as it: (1) reflects the nature of most CoD events within match play which is reactive in nature and not pre-planned, and (2) elicits greater knee loading (especially in the frontal and transverse planes) than pre-planned CoD (Besier et al., 2001). Biomechanical analysis of unplanned CoD (such as kinetics and kinematics) is essential as performance related measures (such as completion time) do not differ between ACLR and healthy controls (King et al., 2018). Biomechanical variables such as increased centre of mass distance to the knee and/or ankle, reduced anterior pelvic tilt, and increased knee flexion angle and knee adduction moments have previously been shown to exist between ACLR athletes and healthy controls and may relate to risk of future reinjury (King et al., 2021a; Stearns and Pollard, 2013; Marques et al., 2020). However, there are no studies that have examined the effect of VR on unplanned CoD biomechanics in the ACLR population.

Therefore, the aim of this study was to examine if VR effects movement biomechanics in an unplanned CoD task in ACLR reconstructed athletes eight months post-surgery, as compared to healthy controls. It was hypothesised that VR has a negative effect on biomechanical variables associated with ACLR reinjury.

7.2 Methods

ACLR and control athletes were recruited for this cohort study between November 2021 and August 2023. ACLR athletes were recruited from the list of four surgeons at the Sports Surgery Clinic, Dublin, Ireland (R.M., C.M., M.J., D.W.), whilst controls were recruited from advertisements in local sporting teams. The study received ethical approval from the Sports Surgery Clinic Ethics Committee (APMOC9102CSSIVHT).

Participants and setting

The study was completed in a sports medicine facility in Dublin, Ireland. A priori sample size calculation with estimated medium effect size of 0.3, significance level of 0.05, power of 80% and numerator degrees of freedom of 1 led to a total sample size of 90 participants being required. ACLR participants were included if they played a multidirectional field-based sport and intended to return to the same level of sport or higher. All ACLR participants underwent primary ACLR with a bone-patellar tendon-bone autograft and were returning to recreational club-level sport. They were at least seven months post-surgery and were already completing multi-direction running with their rehabilitation provider and/or had returned to team training. Participants who had concomitant ligament repairs or previous surgeries to the lower limb were excluded from the study. Controls were included in the study if they were currently engaged in multidirectional field-based sports, had no lower limb injury in the last three months and had no history of lower limb surgery. Controls were recruited from local sporting teams. Controls and ACLR participants were not matched for age or sport. Participants were also excluded if they did not want to wear a blindfold during the stepdown balance task. Participants completed the International Knee Documentation Committee (IKDC) Subjective Knee Form (Higgins et al., 2007) to assess self-reported knee function and the ACL Return to Sport After Injury (ACL-RSI) scale (Webster and Feller, 2021; Kim et al., 2022) to determine ACLR participants' knee confidence and psychological

readiness for return to sport. Both questionnaires are scored between 0 and 100, whereby a higher score denotes greater self-reported knee function (IKDC) or confidence psychological readiness for a return to sport (ACL-RSI). All participants provided informed written consent prior to participation in the study.

Protocol

Participants were tested in a biomechanics laboratory utilising an eight-camera motion analysis system (200Hz; Bonita-B10, Vicon, UK) synchronised (Vicon Nexus 1.8.5) with integrated force plates (two force plates each 40x60 centimetres, 1000Hz BP400600, AMTI, USA) and recording 24 reflective markers. The markers were fixed to the bony landmarks of the trunk, pelvis and lower limb. Participants utilised their own footwear during the change of direction trials with the markers fixed to this. A modified plug-in gait marker set was utilised (Marshall et al., 2014). A software package (Nexus 1.8.5, Vicon Motion Systems, UK) was utilised to collect the biomechanical and GRF data. The biomechanics lab was calibrated at the start of each test to ensure consistency of the collected data. Participants performed a stepdown test to identify VR and an unplanned 90° change of direction task. A standardised 5 minute warmup was conducted by all participants prior to all trials. They completed body ten bodyweight squats, three double leg countermovement jumps, three single leg countermovement jumps for each leg, three double leg drop jumps and three single leg drop jumps for each leg.

Stepdown test to identify VR

A stepdown test on to a single-leg, assessing time to stability after stepping off a 20cm step, is reliable: (i) with full vision in an ACLR population (Colby et al., 1999), and (ii) when completed with both full vision and whilst blinded to derive a VR index score in healthy individuals (**Chapter 3**). The stepdown test was utilised to categorise participants as being visually reliant or not.

Participants were barefoot. A 20cm step was placed behind the dual force plates. Participants placed their hands on their hip and stepped off the step with a single leg and upon landing on the force plate, attempted to achieve stability as quickly as they could for 20 seconds. The single leg landing posture was not standardised for trials; participants were allowed to adopt a strategy that suited them. Participants were asked to keep their head up and their eyes looking forwards. Three successful trials were completed for each leg (ACLR cohort: ACLR limb and uninjured limb; controls: dominant [DM] and non-dominant [NDM]) in each condition (full vision and blinded vision), with two warmup trials provided for each leg. A maximum of six trials were needed to achieve the three successful trials, which avoided fatigue becoming a limiting factor. For the blinded vision trials, participants were blindfolded.

Trials were deemed invalid if the participants removed their hands from their waist, placed their non-testing leg on the ground, shuffled the testing foot on the force plate after landing or removed their blindfold during a trial. Participants removed their blindfold to step back up on the box. Time to stability (TTS) was measured in the medial to lateral direction. A VR index score was calculated utilising TTS under full vision and blinded conditions. A positive VR index value indicates greater VR. A VR index score above zero was used to classify if a participant was VR.

$$VR\ index = \left(\frac{[TTS\ (blinded) - TTS\ (full\ vision)]}{TTS\ (full\ vision)}\right)\ x\ 100$$

Due to the exploratory nature of the study, the cutoff for determining if a participant was VR or not was set at zero. Therefore, any positive VR index scores meant participants were VR and a negative VR index score meant participants were NVR

Unplanned 90° change of direction

The testing procedure for the unplanned CoD task has previously been described (King et al., 2018; Miles et al., 2022) (Figure 7.2). Participants ran forwards five metres as fast as they could to the force plates. Three metres from the force plates a trigger gate (Smartspeed Plus, VALD)

triggered a light on either the left or right exit gates (spaced two metres from the forces plates) which indicated the direction in which the participant was required through. The angle of cut was 90° as it has previously been demonstrated to identify differences in biomechanics between ACLR and healthy controls and some of these differences have been suggested to increase the risk of ACLR reinjury (King et al., 2021b; King et al., 2021a; King et al., 2018; King et al., 2019; Pasanen et al., 2025). The sequence for left and right cuts was randomly assigned by the software. Participants were cued to complete the task as quickly as possible. To assist with this, they were told to 'not slow down prior to passing through the left or right exit gates'. If the left exit gate was triggered, then participants were to cut in that direction utilising their outside foot (e.g. pushing off their right leg to cut to the left). Participants were provided with three warm up trials in each direction. Three valid trials were collected for each direction. A trial was deemed invalid if participants cut in the wrong direction, did not have their whole foot on the force plate when cutting or had a double foot contact on the force plate (e.g. cutting foot planting, lifting off and then planting again on the force plate).

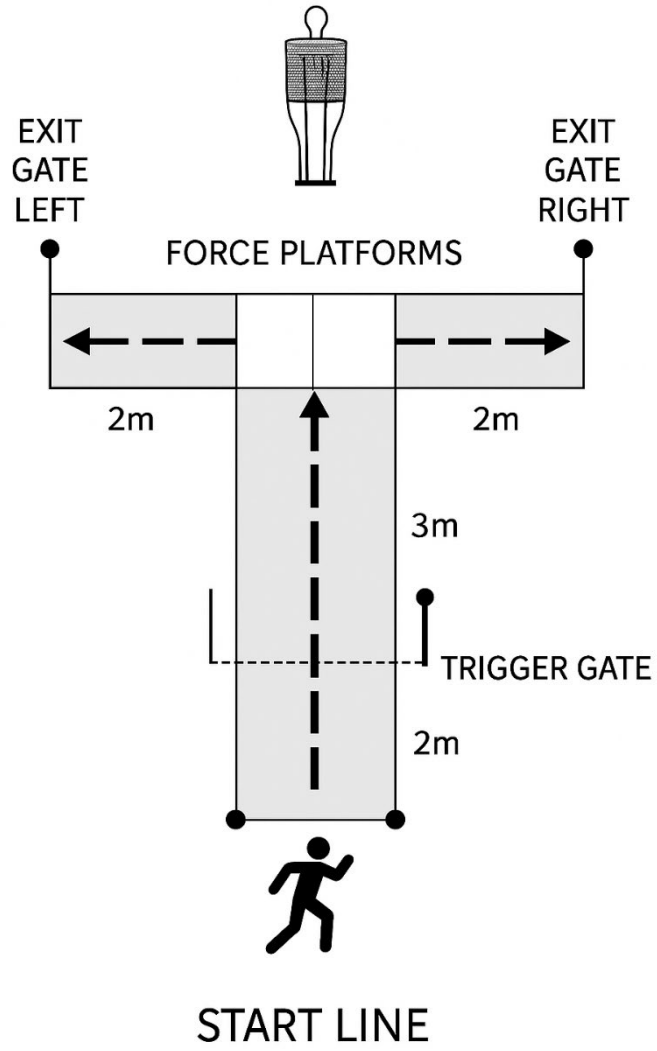


Figure 7.2. Experimental setup for unplanned 90° change of direction task

Data processing and variable selection

Vicon Nexus (Nexus version 2.12) was used to process kinetic and kinematic data. The data were passed through a fourth-order zero lag, low pass filter, with a cut-off frequency of 15 Hz. The trials were subsequently gap-filled using a custom MatLab GUI, manually cleaned and then PiG and filtered. A custom python code (Python version 3.7) was used to extract all variables of interest from each specific c3d cut trial. We defined initial contact as GRF greater than or equal to 20N and

similarly toe off was identified when the GRF was less than or equal to 20 N. Peak knee flexion during the stance phase was defined as the end of the eccentric phase (Li and Qian, 2025; Singh et al., 2025). The average for each leg and trial was also calculated. All extracted data were subsequently exported and saved to and excel sheet using the custom python code.

Biomechanical variables utilised for analysis in this study were selected following a review of the literature (see Table 7.2 and Chapter 2 Section 13). There are limited studies investigating prospectively the risk factors for ACLR reinjury during a change of direction task (King et al., 2021a). Similarly, there are also a limited number of studies investigating ACLR reinjury risk factors of injury in a retrospective manner (King et al., 2018; Miles et al., 2022; Marques et al., 2020; Stearns and Pollard, 2013). Because of this, biomechanical variables associated with reinjury and differences between ACLRs and healthy controls via other movements, such as jump testing (Hewett et al., 2005) and invitro studies (Markolf et al., 1995) were also utilised. This led to 18 variables being selected *a priori* (Table 7.2). GRF variables were reported relative to body mass of the participants. The peak value of each variable was defined as the peak value throughout the full stance phase. Eccentric values for GRF were defined as the average value from initial contact to peak knee flexion angle (Li and Qian, 2025; Singh et al., 2025). Range of motion (ROM), in the case of the trunk side flexion variable, was defined as the absolute change from initial contact to the value at peak knee flexion angle. Anterior knee force was defined as the anterior-posterior component of the net knee joint reaction force calculated using inverse dynamics in Vicon Nexus (Nexus version 2.12). The resultant knee joint reaction force vector was resolved into the local coordinate system on the tibia. The component acting along the anterior-posterior axis was extracted with a positive value indicating anterior knee force and a negative value indicating posterior knee force.

Statistical analysis

Previous studies have demonstrated no asymmetries in biomechanical variables during change of direction (Bencke et al., 2013; Greska et al., 2017), therefore the control group's limbs were analysed separately. This allowed for larger numbers in the CONTROL VR and NVR groups for analysis. For the ACLR VR and NVR groups, only the participants' ACLR limbs were analysed. The final numbers for the analysis were: 37 ACLR VR, 18 ACLR NVR, 50 CONTROL VR and 44 CONTROL NVR.

Approach speed has previously been shown to affect planting foot biomechanics during change of direction (Dos'Santos et al., 2018) and was therefore utilised as a covariate in the analysis. Any outliers in the data were removed following inspection of box and whisker plots and assessing for studentised residuals being greater than ±3 standard deviations. Therefore, a two-way ANCOVA was performed with group (ACLR or CONTROL) and condition (VR or NVR) as the two factors to determine if there was an interaction effect on the selected biomechanical variables. Any outliers in the data were removed following inspection of box and whisker plots and assessing for studentised residuals being greater than ±3 standard deviations. There was homoscedasticity within groups as assessed by visual inspection of the studentised residuals plotted against the predicted values for each group. If a significant interaction ($p<0.05$) effect was identified for a biomechanical variable, then further analysis via simple main effects was conducted. If no interaction effect was identified, then main effects of both group and condition were analysed. Significance level was set at 0.05 and effect sizes were reported with partial η^2 in which 0.01-0.06 indicated small effects size, 0.06-0.14 indicated medium effect size and greater than 0.14 indicated large effect size (Cohen, 2013; Lakens, 2013).

A two-way ANOVA was performed with group (ACLR or CONTROL) and condition (VR or NVR) as the two factors to determine if there was an interaction effect or main effect on approach speed. To determine if any differences existed between the groups (ACLR and CONTROL) with

regards to IKDC and ACLR-RSI scores, independent t-tests were completed. Significance was set at $p<0.05$ and effect sizes were calculated with Cohen *d*, using small (<0.5), medium (0.5-0.8) and large (>0.8) classifications (Sullivan and Feinn, 2012).

Table 7.2 List of biomechanical variables that were assessed. Relevant references have been listed for the identified risk factors of reinjury.

Biomechanical risk factor	**Reference**
GRF	
Medial GRF at IC*	(King et al., 2018)
Posterior GRF at IC*	(Garcia et al., 2022)
Vertical GRF at IC*	(King et al., 2018)
Medial GRF during eccentric phase*	(King et al., 2018)
Posterior GRF during eccentric phase*	(Garcia et al., 2022)
Vertical GRF during eccentric phase *	(King et al., 2018)
Kinematics	
Increased trunk side flexion ROM	(King et al., 2021a)
Increased anterior pelvic tilt at IC	(King et al., 2021a)
Reduced knee flexion angle at IC	(Bosio et al., 2022)
Reduced peak knee flexion angle	(King et al., 2019)
Increased knee valgus at initial contact	(Bosio et al., 2022)
Increased knee valgus ROM	(Hewett et al., 2005)
Increased COM to knee in frontal plane	(King et al., 2021a)
Increased COM to ankle in frontal plane	(King et al., 2021a)

Kinetics	
Reduced knee extensor moment at IC	(King et al., 2018)
Increased peak anterior knee force during eccentric phase	(Markolf et al., 1995)
Reduced peak knee flexor moment	(Hart et al., 2015)
Increased knee valgus moment at IC	(King et al., 2018)
Increased knee valgus moment at peak knee flexion	(King et al., 2018)

Abbreviations: IC= initial contact, GRF= ground reaction force, ROM= absolute change from value at initial contact to value at peak knee flexion angle, COM= centre of mass and *= literature unclear as to whether an increase or reduction in the variable is related to reinjury.

7.3 Results

102 male participants aged between 18 and 36 years of age were included in the study (Table 7.3.A). Independent t-tests demonstrated no significant difference existed in age, height, mass and Tegner score between the 55 ACLR participants and 47 healthy controls. The ACLR group scored significantly lower on the IKDC (t=-13.13, Cohen's d= -2.61, p<0.001) and the ACL-RSI questionnaire (t=-10.44, Cohen's d= -2.07, p<0.001). A two-way ANCOVA (utilising approach speed as a covariate) was conducted to examine the effects of group and condition on ground reaction force, kinematic and kinetic variables (see Table 7.3.B). The approach speed for each group was as follows: ACLR VR=2.25 ± 0.05 metres/second (m/s), ACLR NVR= 2.42 ± 0.07m/s, CONTROL VR= 2.38 ± 0.04m/s and CONTROL NVR= 2.36 ± 0.04m/s. A two-way ANOVA was performed to examine the effects of group and condition on approach speed. No significant interaction effect or main effect was present between group and condition on approach speed.

Table 7.3.A. Participant demographics. Mean values presented with standard deviation in paratheses.

	ACLR	Controls	Significance (p value)
Number	55	47	
Age (years)	24.7 (4.2)	24.3 (2.9)	0.59
Height (cm)	183.2 (7.8)	182.8 (7.5)	0.92
Mass (kg)	84.0 (6.2)	85.2 (6.0)	0.24
Time post-surgery (months)	8.7 (1.4)		
IKDC	83.5	99.4	<0.001
ACL-RSI	67.9	93.4	<0.001
Tegner score	7.0 (0.8)	6.9 (0.8)	0.16

Abbreviations: cm= centimetres, kg= kilograms, IKDC= International knee documentation committee subjective knee form, ACL-RSI= ACL return to sport after injury scale

Ground reaction force

No significant interaction was present between group and condition on posterior, medial and vertical GRF at initial contact. The main effect of condition showed a significant difference, with those being VR demonstrating lower vertical GRF at initial contact (VR= 0.76 N/kg [95% CI 0.70 to 0.81 N/KG] and NVR= 0.89 N/kg [95% CI 0.83 to 0.96], p=0.003). No significant main effect was noted for group on vertical ground reaction force at initial contact. Similarly, no significant difference was noted for group and condition for medial and posterior GRF at initial contact.

When examining the GRF during the eccentric phase, a significant interaction was present between group and condition on vertical (F[1,143]= 8.313, p= 0.005, partial η^2=0.055) GRF and medial (F[1,143]= 4.131, p= 0.044, partial η^2=0.028), but not the posterior GRF. Simple main

effects demonstrated the ACLR VR (13.52N/kg [95% CI 13.05-13.99N/kg]) had significantly lower vertical GRFs during the eccentric phase as compared to the ACLR NVR (14.50N/kg [95% CI 13.83 to 15.17N/kg]) (F[1,143]= 5.725, p<0.018, partial η^2=0.038). Simple main effects also demonstrated that the ACLR VR (13.52N/kg [95% CI 13.05 to 13.99N/kg]) had significantly lower vertical GRFs during the eccentric phase as compared to the CONTROL VR (14.67N/kg [95% CI 14.26 to 15.07N/kg]) (F[1,143]= 13.261, p<0.001, partial η^2=0.085). Similarly, simple main effects demonstrated the ACLR VR (5.40N/kg [95% CI 5.06 to 5.73N/kg]) had significantly lower medial GRF during the eccentric phase as compared to the CONTROL VR (6.15N/kg [95% CI 5.86 to 6.44N/kg]) (F[1,143]= 11.144, p=0.001, partial η^2=0.072).. No main effects were seen in the posterior GRF during the eccentric phase.

Kinematics

Trunk side flexion ROM and anterior pelvic tilt at initial contact demonstrated no significant interaction effect. An analysis of the main effects for both group and condition also demonstrated no significant effect for both variables. Knee flexion angle at initial contact demonstrated a significant interaction effect between group and condition (F[1,142]=3.945, p=0.049, partial η^2=0.027). Simple main effects demonstrated the ACLR VR (36.83° [95% CI 34.25 to 39.41°]) exhibiting significantly less knee flexion than the CONTROL VR (39.33° [95% CI 37.14 to 41.52°]) (F[1,142]= 13.131, p<0.001, partial η^2=0.085). With regards to peak knee flexion angle, there was no interaction effect between group and condition. There was a main effect for group with ACLR participants (62.64° [95% CI 60.99 to 64.28°]) having reduced knee flexion as compared to CONTROLS (70.64° [95% CI 69.46 to 71.82°]) (F[1,143]= 59.339, p<0.001, partial η^2=0.293). With regards to knee valgus at initial contact, no interaction effect was present between group and condition. However, a main effect was present with the VR group (3.15° [95% CI 1.88 to 4.43°]) exhibiting greater knee valgus than the NVR group (-0.57° [95% CI -2.26 to1.12°]) (F[1,134]= 12.143, p<0.001, partial η^2=0.083). Knee valgus ROM demonstrated no interaction effect between

group and condition but a main effect was present with the VR group (5.26° [95% CI 4.73 to 5.80°]) exhibiting greater knee valgus than the NVR group (4.28° [95% CI 3.59 to 4.98°]) (F[1,138]= 4.901, p= 0.028, partial η^2=0.034). With regards the distance from COM to knee in the frontal plane, a significant interaction effect was present between group and condition (F[1,142]= 4.960, p= 0.028, partial η^2=0.034). Simple main effects demonstrated ACLR VR (4.03% [95% CI 3.43 to 4.63%]) were significantly less than ACLR NVR (5.71% [95% CI 4.87 to 6.56%]) ((F[1,142]= 10.420, p= 0.002, partial η^2=0.068). The distance from COM to ankle in the frontal plane demonstrated no interaction effect between group and condition but a main group effect demonstrated that the VR group (8.74% [95% CI 7.94 to 9.55%]) had significantly lower distance than the NVR group (10.67% [95% CI 9.64 to 11.70%]) (F[1,143]= 8.841, p= 0.004, partial η^2=0.056).

Kinetics

Knee extensor moment at initial contact demonstrated a significant interaction effect was present between group and condition (F[1,140]= 8.680, p=0.004, partial η^2=0.058). Simple main effects analysis demonstrated that the ACLR VR (1.23 Nm/kg [95% CI 1.10 to 1.35 Nm/kg]) had significantly greater knee extensor moment than ACLR NVR (0.90 Nm/kg [95% CI 10.73 to 1.07 Nm/kg]) ((F[1,140]= 9.342, p= 0.003, partial η^2=0.063). With regards to the peak anterior knee force during the eccentric phase, a significant interaction effect was present between group and condition (F[1,140]= 4.317, p<0.040, partial η^2=0.030). Simple main effects demonstrated that the ACLR VR (8.24 N/kg [95% CI 7.68 to 8.80 N/kg]) had a significantly reduced peak anterior knee force than ACLR NVR (9.43 N/kg [95% CI 8.62 to 10.23 N/kg]) and CONTROL VR (10.68 N/kg [95% CI 10.20 to 11.15 N/kg]) ((F[1,140]= 5.820, p=0.017, partial η^2=0.040) and (F[1,140]= 42.775, p<0.001, partial η^2=0.234), respectively). Knee flexor moment demonstrated a significant interaction effect was present between group and condition (F[1,140]= 6.023, p=0.015, partial η^2=0.041). Simple main effects analysis demonstrated that the ACLR VR (1.32 Nm/kg [95% CI 1.21 to 1.43 Nm/kg]) had significantly greater peak knee flexor moment than the ACLR NVR (1.08

Nm/kg [95% CI 0.92 to 1.23 Nm/kg]) ($F[1,140]= 6.267$, $p= 0.013$, partial $\eta^2=0.043$). Knee valgus moment at initial contact and knee valgus moment at peak knee flexion demonstrated no interaction effect between group and condition. Whilst no main effect was present for knee valgus moment at initial contact, a main effect was present for knee valgus moment at peak knee flexion with the VR group (0.92 Nm/kg [95% CI 0.82 to 1.02 Nm/kg]) having significantly less knee valgus moment than the NVR group (1.11 Nm/kg [95% CI 0.98 to 1.24 Nm/kg]) ($F[1,141]= 5.215$, $p=0.024$, partial $\eta^2=0.036$).

Table 7.3.B. Descriptive statistics, interaction effect and main group effects of 2 x 2 ANCOVA

Variable	ACLR VR	ACLR NVR	Control VR	Control NVR	Interaction effect			Main effect (ACLR and control)			Main effect (VR and NVR)		
	M (SE)	M (SE)	M (SE)	M (SE)	F (df)	p	partial η^2	F (df)	p	partial η^2	F (df)	p	partial η^2
GRF													
Medial GRF at IC (N/kg)	0.204 (0.051)	0.207 (0.074)	0.203 (0.043)	0.298 (0.046)	0.703 (1,142)	0.403	0.005	0.657 (1,142)	0.419	0.005	0.805 (1,142)	0.371	0.006
Posterior GRF at IC (N/kg)	0.281 (0.032)	0.280 (0.046)	0.279 (0.027)	0.277 (0.029)	0.001 (1,141)	0.997	<0.001	0.004 (1,141)	0.947	<0.001	0.002 (1,141)	0.963	<0.001
Vertical GRF at IC (N/kg)	0.702 (0.043)	0.926 (0.060)	0.812 (0.036)	0.863 (0.038)	3.694 (1,140)	0.057	0.026	0.253 (1,140)	0.616	0.002	**9.304 (1,140)**	**0.003**	**0.062**
Medial GRF during eccentric phase (N/kg)	5.397 (0.170)	5.861 (0.242)	6.150 (0.146)	5.878 (0.156)	**4.131 (1,143)**	**0.044**	**0.028**	**4.252 (1,143)**	**0.041**	**0.029**	0.282 (1,143)	0.596	0.002
Posterior GRF during eccentric phase (N/kg)	4.879 (0.156)	5.412 (0.222)	5.247 (0.137)	5.197 (0.143)	3.063 (1,141)	0.082	0.021	0.199 (1,141)	0.656	0.001	2.114 (1,141)	0.148	0.015
Vertical GRF during eccentric phase (N/kg)	13.521 (0.237)	14.499 (0.337)	14.665 (0.204)	14.186 (0.217)	**8.313 (1,143)**	**0.005**	**0.055**	2.569 (1,143)	0.111	0.018	0.984 (1,143)	0.323	0.007
Kinematics													
Trunk side flexion ROM (°)	4.553 (0.377)	3.944 (0.572)	4.845 (0.315)	4.556 (0.344)	0.152 (1,136)	0.697	0.001	1.142 (1,136)	0.287	0.008	1.190 (1,136)	0.277	0.009
Anterior pelvic tilt at IC (°)	9.914 (0.755)	6.967 (1.136)	8.723 (0.662)	8.545 (0.744)	2.721 (1,133)	0.101	0.20	0.051 (1,133)	0.822	<0.001	3.449 (1,133)	0.065	0.025
Knee flexion angle at IC (°)	36.827 (1.305)	36.773 (1.834)	39.330 (1.106)	44.741 (1.180)	**3.945 (1,142)**	**0.049**	**0.027**	13.703 (1,142)	<0.001	0.088	3.791 (1,142)	0.053	0.026

Peak knee flexion angle (°)	62.264 (0.948)	63.018 (1.348)	69.331 (0.814)	71.950 (0.868)	0.855 (1,143)	0.357	0.006	**59.339 (1,143)**	**<0.001**	**0.293**	2.795 (1,143)	0.097	0.019
Knee valgus at initial contact (°)	1.865 (0.994)	-2.138 (1.477)	4.443 (0.832)	0.992 (0.880)	0.67 (1,134)	0.796	<0.001	**6.749 (1,134)**	**0.010**	**0.048**	**12.143 (1,134)**	**<0.001**	**0.083**
Knee valgus ROM (°)	5.327 (0.412)	4.256 (0.597)	5.200 (0.357)	4.309 (0.379)	0.041 (1,138)	0.840	<0.001	0.007 (1,138)	0.936	<0.001	**4.901 (1,138)**	**0.028**	**0.034**
COM to knee in frontal plane (% height)	4.030 (0.305)	5.714 (0.429)	3.526 (0.259)	3.777 (0.276)	**4.960 (1,142)**	**0.028**	**0.034**	**13.612 (1,142)**	**<0.001**	**0.087**	**9.049 (1,142)**	**0.003**	**0.060**
COM to ankle in frontal plane (% height)	9.203 (0.620)	12.387 (0.883)	8.284 (0.532)	8.946 (0.568)	3.650 (1,143)	0.058	0.025	**10.285 (1,143)**	**0.002**	**0.067**	**8.481 (1,143)**	**0.004**	**0.056**
Kinetics													
Knee extensor moment at IC (Nm/kg)	1.225 (0.062)	0.902 (0.087)	1.142 (0.053)	1.204 (0.056)	**8.680 (1,140)**	**0.004**	**0.058**	2.658 (1,140)	0.105	0.019	**4.043 (1,140)**	**0.046**	**0.028**
Peak anterior knee force in the eccentric phase (N/kg)	8.240 (0.285)	9.428 (0.407)	10.675 (0.238)	10.611 (0.254)	**4.317 (1,140)**	**0.040**	**0.030**	**34.352 (1,140)**	**<0.001**	**0.197**	3.483 (1,140)	0.064	0.024
Peak knee flexor moment (Nm/kg)	1.319 (0.057)	1.077 (0.079)	1.212 (0.048)	1.263 (0.052)	**6.023 (1,140)**	**0.015**	**0.041**	0.412 (1,140)	0.522	0.003	2.527 (1,140)	0.114	0.018
Knee valgus moment at IC (Nm/kg)	0.294 (0.065)	0.217 (0.093)	0.242 (0.056)	0.266 (0.060)	0.520 (1,143)	0.472	0.004	<0.001 (,143)	0.984	<0.001	0.142 (1,143)	0.707	0.001
Knee valgus moment at peak knee flexion (Nm/kg)	0.745 (0.080)	0.869 (0.112)	1.096 (0.067)	1.356 (0.072)	0.649 (1,141)	0.422	0.005	**23.543 (1,141)**	**<0.001**	**0.143**	**5.215 (1,141)**	**0.024**	**0.038**

Abbreviations: M= mean, SE= standard error, df= degrees of freedom, p= level of significance, IC= initial contact, VR= visual reliance, NVR= non-visual reliance, GRF= ground reaction force, COM= centre of mass, N/kg= Newton per kilogram, °= degrees, Nm/kg= Newton metres per kilogram, % height= distance as a percentage of participant height

7.4 Discussion

The aim of the study was to examine if VR affects movement biomechanics in an unplanned CoD task in ACLR athletes eight months post-surgery. It was hypothesised that VR would have a negative effect on biomechanical variables associated with increased risk of reinjury. The results of the study demonstrate that VR does affect unplanned change of direction biomechanics but, in contrast to our hypothesis, more biomechanical changes are indicative of being protective from injury than increasing the risk of injury. For example, ACLR VR participants demonstrated reduced peak anterior knee force during the eccentric phase, greater knee extensor moment at IC, greater peak knee flexor moment, and reduced distance from COM to knee in the frontal plane as compared to ACLR NVR (King et al., 2021a; Markolf et al., 1995). This was further supported by reduced knee valgus moment at peak knee flexion (Hewett et al., 2005; Stearns and Pollard, 2013) and reduced distance from COM to ankle in the frontal plane (King et al., 2021a) in VR participants as compared to NVR in both groups. ACLR VR participants also demonstrated reduced vertical GRF at IC, reduced vertical GRF during eccentric phase, reduced medial GRF during eccentric phase as compared to ACLR NVR which some have labelled as either potentially increasing and decreasing the risk of reinjury (King et al., 2021a).

In the following discussion, the findings from the present study on how VR affects movement biomechanics cannot be directly compared to other studies because no previous studies have examined the effect of VR on movement biomechanics. Therefore, comparisons to previous studies are only possible in relation to the difference between ACLRs and controls (either against their own uninjured limb or a separate uninjured control group).

An athlete's movement strategy can have a large effect on the risk of ACL injury because it influences the rate and magnitude of loading placed on the ACL (Boden et al., 2000; Bertelsen et al., 2017). Previously, sagittal and frontal plane kinematics, such as increased distance from the COM to the ankle and knee, increased knee valgus at initial contact, increased knee valgus ROM

and reduced knee flexion angle at initial contact, have been suggested as risk factors for ACLR reinjury (King et al., 2021a; Clark et al., 2019; Leppänen et al., 2016; Olsen et al., 2004). Our ACLR VR group exhibited significantly greater knee flexion at initial contact and less distance from the COM to the knee in the frontal plane, as compared to the ACL NVR, which suggests that they employ a strategy that places lower load on the ACL (Marques et al., 2020; Belkhelladi et al., 2025). This was further supported by the ACLR VR group demonstrating reduced peak anterior knee force, medial GRF and vertical GRF during the eccentric phase as compared to ACLR NVR, again indicating that they are protecting the ACL by reducing the load through the planting leg and thereby the ACL (Bosio et al., 2022; King et al., 2021a). The ACLR VR group also had larger knee extensor moment at initial contact and peak knee flexor moment as compared to the ACLR NVR group. The ACLR VR values tended to be similar to that of the CONTROL group, which may suggests that ACLR VR movement strategy was resulting in muscle loading that would reduce loading on the ACL and hence reduce the risk of reinjury (Chijimatsu et al., 2025; Kuenze et al., 2015). When examining kinematics, there were contrasting findings. The VR group exhibited greater knee valgus at initial contact and ROM between initial contact and peak knee flexion, which can place greater loads on the ACL (Hewett et al., 2005). However, the VR group had a smaller distance from the COM to the ankle in the frontal plane as compared to the NVR group which may place lower loads through the ACL (Donelon et al., 2020). While VR affected biomechanical variables related to movement strategy that are related to both reduced risk of ACLR reinjury and those that increase the risk, there are more variables that would suggest that VR is protective of future ACLR reinjury. The results of the present study suggest that VR overall is more protective in ACLR athletes in a lab-based CoD task which runs counter to both our hypothesis and the suggested theory that VR increases the risk of ACLR reinjury (Grooms et al., 2015a; Grooms et al., 2015c; Swanik, 2015).

Interpreting the possible implications of our findings requires consideration of the absolute and relative sensory contribution from vision and proprioception during the execution of a movement.

Whilst the visual system is the dominant sensory system utilised during the execution of a movement (Corlett, 1992; Li et al., 2017), the motor planning centres require adequate proprioceptive input to understand the body's starting and ongoing posture (Davids et al., 2012; Gibson, 1986; Renshaw et al., 2022). Following an ACLR, there is reduced proprioceptive information arising from the knee for several months whilst the proprioceptors rennervate the ACL graft (Dhillon et al., 2012; Dhillon et al., 2011). During this period, the motor planning centres likely become more reliant on the visual system (Criss et al., 2020; Grooms et al., 2017) whilst the relative and absolute contribution of proprioceptive information to motor planning and execution reduces. Following approximately seven months post-surgery, proprioceptive function has mostly or fully normalised in the knee (Vitharana et al., 2024; Mir et al., 2008; Ozenci et al., 2007), however, athletes may stay VR as they have developed this system more during the rehabilitation process. This theoretical framework can be found in Figure 7.4. It is believed that VR leads to increased processing demands within the motor planning centres because athletes are processing more visual information as compared to proprioceptive information during movements than they previously would have prior to ACL injury (An et al., 2019; Swanik, 2015). Therefore, our results can be interpreted in two ways: (1) VR is protective in ACLR athletes, or (2) the task utilised in this study, lab-based unplanned CoD task, does not appropriately challenge the motor planning centres in ACLR athletes with VR. A potential reason why VR ACLR athletes may have demonstrated a more protective biomechanical technique could be because athletes regularly perform high intensity and complex movements in chaotic sporting environments (Bloomfield et al., 2007), hence our assessment task had lower visual complexity and processing requirements (one triggered light stimulus). Therefore, being VR resulted in them being able to process and utilise more visual information than the ACLR NVR participants (see Figure 7.4). However, in real-world sporting environments (match play and training sessions), athletes are required to process multiple visual stimuli simultaneously and make multiple decisions (Buscemi et al., 2024; Lochhead et al., 2024) which place additional processing demands within the motor control

centres and thereby reduces the absolute amount of sensory information the athlete can utilise for the execution of movement (Lachter et al., 2004). This change also leads to an increase in the relative contribution of proprioception in both the VR and NVR ACLR athletes. However, because VR ACLR athletes continue to use relatively more visual information than proprioceptive information as compared to NVR ACLR athletes, they may employ a suboptimal movement technique due being unable to process enough of the visual information present. This could thereby result in excessive loading on the ACL and increase the risk of ACLR reinjury. This is supported by studies investigating the addition of increased visual attention demands (increased visual stimuli within the motor task) in jumping and CoD tasks in healthy controls which showed an increase in biomechanical factors related to ACL injury (Bertozzi et al., 2023; Monfort et al., 2019). Monfort and colleagues (2019) demonstrated that worse visual-spatial memory was associated with increased peak knee valgus angle during a 45° CoD whilst dribbling a soccer ball. Similarly, a study (Herman and Barth, 2016) as part of Bertozzi and colleagues (2023) review demonstrated that individuals who demonstrated lower scores on a neurocognitive test demonstrated larger vertical ground reaction force and larger knee anterior shear force during a reactive drop jump task (in response to a visual stimuli). The increased visual attention demands altering biomechanics is potentially the result of filters within the motor control centres blocking what it perceives to be 'irrelevant' stimuli due to a noisy or busy environment, as described by selective filter theory (Broadbent, 1958; Lachter et al., 2004).

Future research should follow ACLR VR athletes prospectively to determine if they are at greater or lesser risk of ACLR reinjury as compared to ACLR NVR athletes, both in terms of the prevalence of reinjury and the movement technique adopted in competitive sporting environments. Similarly, there may be similar implications of this study's findings to the occurrence of primary ACL injuries, as VR and NVR were also evident in the CONTROLS.

ACLR reinjury rates have not diminished over the last 20 years and remain relatively high at 8%, with even higher rates (up to 28%) amongst younger athletes (Arundale et al., 2018; King et al., 2021b; King et al., 2021a; Rodriguez-Merchan and Valentino, 2022; Wiggins et al., 2016; Webster and Feller, 2016). Athletes are three times more likely to sustain an ACL injury during competitive match play as compared to training sessions (Joseph et al., 2013) which suggests the rapid contextual decision-making required in competitive match play and higher intensity may influence ACLR reinjury. It has been suggested that VR can result in errors during dual-task activities whilst balancing (Bodkin et al., 2021) and hopping (Ricupito et al., 2025), although these studies did not directly measure whether the participants had VR. Whilst our results demonstrated ACLR VR participants employing a more protective strategy than ACLR NVR participants, this could be the result of a lack of dual-task components within the assessment task utilised and thereby allowing ACLR VR participants to process the visual information more effectively. Therefore, increasing the dual-task conditions of the assessment task to reflect more real-world situations may increase the processing demands on ACLR VR participants and overload their visual processing centres and lead to errors in movement strategy that may increase the risk of ACLR reinjury. Future studies should investigate whether lab-based CoD tasks with additional dual-task stress results in ACLR VR participants demonstrating biomechanics related to ACLR reinjury.

Visual and proprioceptive information utilised in the execution of movement

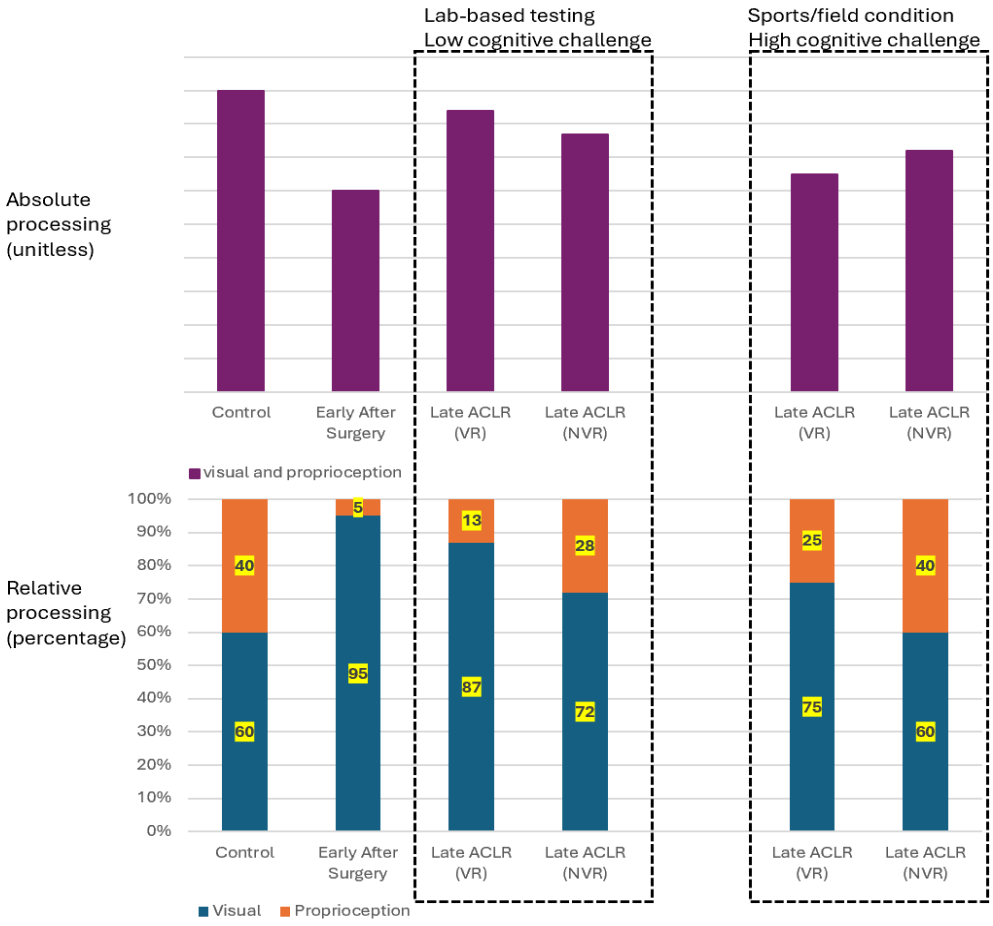


Figure 7.4. The theoretical framework detailing how visual and proprioceptive information is utilised both absolutely and relatively early post-surgery and late post-surgery during a lab-based movement and a movement on a sporting field. Abbreviations: ACLR= anterior cruciate ligament reconstruction, VR= visual reliance and NVR= non visual reliance

Study Implications

The implications of the study are that VR changes the unplanned CoD biomechanics of ACLR athletes. As this is the first study to examine CoD biomechanics in ACLR VR participants and demonstrated results opposite to the theoretical VR framework suggested by other authors (Grooms et al., 2018; Vitharana et al., 2025a; Swanik, 2015), clinicians should have be open-minded that VR may be protective. To date, no study has examined methods to increase or decrease VR in ACLR athletes. Therefore, clinicians may need to explore different rehabilitation methods to affect a change in VR. It has been suggested that methods such as internal focus

during exercises and mental visualisation practice of movement task may increase VR (Ma et al., 2022; Gokeler et al., 2019; Swanik, 2015). Therefore, if a ACLR NVR athlete is identified, clinicians may look to prescribe daily mental visualisation of high loading tasks such as CoD or landing. Similarly, when performing CoD or landing tasks, clinicians may encourage a prescriptive coaching style so that athletes focus on their body segments, such as the knee, to gain a sense of what the segment movement should look and feel like when completing the task. However, because the results of this study challenge the established framework, clinicians should challenge ACLR VR athletes with assessments reflective of real-world situations and dual-task assessments to determine if their movement strategy is negatively impacted (Grooms et al., 2015a; Gokeler et al., 2019; Vitharana et al., 2025b). If VR is detrimental to an ACLR athlete as suggested in the prior framework, then clinicians should employ rehabilitation methods that reduce VR. These methods may include visual distraction, proprioceptive training and having an external focus during movements (Gokeler et al., 2019; Grooms et al., 2015a). There is a lack of evidence of the effectiveness of these strategies in reducing VR but they have been suggested to increase the motor control centres' use of proprioceptive information during the execution of movements (Grooms et al., 2015a).

A limitation of the study was that variables were analysed at discrete points of the stance phase: initial contact and peak knee flexion, which represent two important time points of stance (initial loading and the end of the eccentric phase, respectively). Therefore, information outside of these points are somewhat lost during analysis. It may be more appropriate to analyse across all timepoints of stance phase via statistical parametric mapping (Miles et al., 2022; King et al., 2019). Another limitation of the study was that although the study was appropriately powered, there was a smaller number of participants in the ACLR NVR group as compared to the other three groups. Whilst there was still a significant interaction found across a number of biomechanical variables, a larger sample size may increase the statistical power for some of the other biomechanical variables that were examined. Also, the study examined VR in a dichotomous

manner (VR or NVR), thereby reducing the amount of information/variation in this independent measure. Future work should explore the relationship between the magnitude of VR and the biomechanics of CoD. A further limitation was that standard error of measurement and minimal detectable change was not calculated for each of the variables examined. Therefore, this does not allow a deeper examination of the differences identified in this study to discern which if the variables demonstrate a clinically significant difference. Future studies should examine the reliability of the CoD task to determine the standard error of measurement and minimal detectable change values of the variables.

7.5 Conclusion

Overall, the results of the study demonstrate that VR affects unplanned CoD movement biomechanics in those with ACLR. However, contrary to the hypothesis, ACLR VR exhibited biomechanics that result predominantly in movement strategies and loading on the ACL that may reduce the risk of reinjury. Future studies need to determine whether VR, as assessed in the current methodology, is ultimately indicative of increasing or decreasing the risk of ACLR reinjury prospectively by following ACLR VR and ACLR NVR groups to determine the rate of reinjury and their movement biomechanics in competitive sporting situations. If VR does increase the risk of reinjury, then more clinically appropriate assessment tasks may need to be developed to understand why it increases the risk of reinjury. This could be achieved by utilising unplanned change of direction with increased visual attention demands or the addition of dual-task stressors.

Chapter 8

Thesis Summary

The primary aim of the thesis was to examine whether visual reliance (VR) following ACLR affects change of direction (CoD) biomechanics. Further to this, secondary aims of the thesis were to determine if VR could be identified with a clinical test and to determine if there was a difference in visual processing ability between ACLR and healthy controls. These were addressed in six research questions (Chapters 3, 4, 5, 6, 7 and A) and a scoping review on afferent dysfunction (within Chapter 2). Case-control studies were utilised within the thesis and demonstrated a number of statistically significant changes in CoD biomechanical technique between ACLR VR athletes and ACLR NVR athletes.

VR has previously been identified in ACLR athletes via specialised assessment technologies such as functional brain MRIs (Chaput et al., 2021a; Criss et al., 2020; Grooms et al., 2017) and electroencephalography (Lehmann et al., 2021a). During simple tasks such as single leg standing or unresisted knee flexion and extension, VR has been demonstrated via the increased activation of the visual processing areas of the brain in ACLR athletes (Grooms et al., 2017; Lehmann et al., 2021a). Clinically, balance testing has been utilised in the chronic ankle instability cohort to identify VR (Kim, 2020a). VR is determined by completing a postural stability task, such as single leg standing, with full vision and then blinded. A worsening in postural stability whilst blinded would indicate the extent of VR. However, a review (Wikstrom et al., 2017) demonstrated that single leg balance was unable to identify VR in ACLR athletes potentially because the task does not challenge the motor planning centres enough. A higher loading, stepdown task, with full vision

and whilst blinded was found to be a reliable method of identifying VR (Chapter 3). It was also shown that ACLR athletes demonstrated VR during the stepdown task in the ACLR limb as compared to the uninjured limb and control limbs (Chapter 4). The VR in the ACLR limb was independent of proprioceptive function as the joint position sense of the knee was no different to that of the uninjured limb and control limbs. This supports the theory suggested by others (Grooms et al., 2015a; Needle et al., 2017) that VR may occur in the early weeks following an ACLR (Lehmann et al., 2021a) but the reliance on visual information remains chronically, even once proprioceptive information has returned back to near preinjury levels. Therefore, clinicians can now utilise the stepdown task during a rehabilitation process to determine if their athletes have VR.

Athletes who scored lower on visual processing ability tests (e.g. visual memory, visual processing speed and reaction time) had an increased risk of sustaining an ACL injury than those athletes who scored higher (Swanik et al., 2007). However, following ACLR, there are limited studies examining whether visual processing abilities differ between ACLRs and healthy controls. The results of the scoping review (Chapter 2) demonstrate that there are mixed findings which may be the result of the heterogeneity of the assessment tools utilised. A suggested solution to varied assessment tools is the use of software systems that assess visual processing abilities across a number of domains such as visual clarity, depth perception and multiple object tracking, as they may relate better to sporting performance (Buscemi et al., 2024; Liu et al., 2020). When tested, no difference was identified between ACLRs and healthy controls across five domains: depth perception, contrast sensitivity, perception span, multiple object tracking and reaction time (Chapter 6). This potentially suggests that whilst ACLR athletes may have VR, their underlying ability to process visual information is not affected. It could also suggest that tablet or computer-based assessments of visual processing are not reflective enough of real-world processing demands in a sporting environment to elicit changes. This is supported by a study (Bodkin et al.,

2021) that demonstrated that ACLR athletes exhibited greater gaze tracking errors than healthy controls when tasked with tracking an object whilst standing on one leg. The dual-task nature and complexity of the task may have challenged the athlete's motor planning and visual processing centres enough to elicit differences.

In the preceding chapters, it was determined that a stepdown task was a reliable measure to identify VR and that ACLR athletes were more VR in the ACLR limb than the uninjured limb and control limbs (Chapters 3 and 4). Also, visual processing abilities did not differ between ACLR athletes and controls (chapter 6). Therefore, the final study was to focus on the effect of VR on biomechanical technique. VR was found to affect the unplanned CoD biomechanics within ACLR athletes (Chapter 7). However, rather than negatively influencing CoD technique, the ACLR VR group was found to employ a movement technique which was more protective in nature and thereby potentially reduce the risk of ACLR reinjury. This was evidenced via several factors such as reduced peak anterior knee force during the eccentric phase, reduced distance of COM to the knee, increased knee flexor/extensor moments and reduced knee valgus moment at peak knee flexion. This study is the only study to have investigated the effect of VR on CoD biomechanics in an ACLR cohort. Previous research has focused predominantly on establishing a link between knee movement and increased brain activity in the visual processing centres rather than examining if VR affects movement. Therefore, there could be two explanations for the results that were reported in Chapter 7: (1) VR is protective in nature by allowing athletes to process more information during a particular movement, or (2) VR is not protective in nature and it was not evident in our results because the assessment task (lab-based unplanned CoD) was not challenging enough, both cognitively and from a sensory input perspective, to see this. To understand both explanations, exploring the absolute and relative contributions of visual and proprioceptive inputs during motor planning and execution is important (see Figure 7.1). Vision is the predominant sensory input when planning a movement (Corlett, 1992; Goodale, 1998; Li et

al., 2017) and provides the athlete with information regarding the environment around them. Meanwhile, proprioceptive sensory input is utilised to provide the motor planning centres with an awareness of the body's posture within the environment (Peterka, 2002). Following an ACLR, there is reduced proprioceptive inputs, thereby resulting in greater reliance on visual information (Grooms et al., 2017). This greater reliance on visual information may increase the processing demands due to the rich sensory information that it provides to the motor planning centres (Chaput et al., 2021a; Criss et al., 2020). However, although proprioceptive input improves, mostly or completely back to preinjury levels, after several months following an ACLR, the motor planning centres may continue to rely on visual information to a greater extent as this pathway has been developed over several months. At this latter stage of rehabilitation, the impact that VR has on an athlete's movement technique may be task-specific. The assessment task utilised in our study, lab-based unplanned CoD, had one visual stimulus for the athletes to focus on (triggered lights) which is commonly utilised in ACLR research (King et al., 2021a; King et al., 2018; King et al., 2019; Miles et al., 2022). However, athletes generally employ complex and high velocity movements in visually rich and chaotic sporting environments after returning to training and competition (Taberner et al., 2025a). Therefore, our assessment task may not place a high cognitive demand on the motor planning centres and hence VR may allow them to employ a more protective movement technique than ACLR NVR athletes as they can effectively process the sensory information. However, if the assessment task was more reflective of real-world sporting situations to include multi-task thinking or decision making, then the processing demands during motor planning would increase (Büchel et al., 2022). The increased processing demands could then result in a reduced capacity to utilise both visual and proprioceptive information. The ACLR VR athletes would be able to process less sensory information (in absolute terms) than the ACLR NVR athletes, as they are utilising relatively more visual information which requires more processing resources. This theoretical framework is presented in Figure 7.1. This inefficiency could result in an athlete employing a suboptimal movement strategy due to the chaotic sporting

environment and thereby increase the risk of ACLR reinjury. This is the only study examining the effect of VR on CoD biomechanics in an ACLR population and because it challenges the current theory of how VR affects athletes, further research is required utilising more challenging assessment tasks to determine if VR is protective in nature or if it does increase the risk of injury when ACLR athletes return to sport.

8.1 Implications

There are a number of implications arising from this thesis for clinicians. One such implication is that clinicians can now utilise a clinically accessible task, the stepdown task (full vision versus blinded), to determine if their patient has VR. Previously, functional brain MRI and electroencephalography was required to identify VR. The stepdown task focused only participants' force data to calculate time to stability and since force plates are increasingly accessible in outpatient rehabilitation clinics, it thereby allows clinicians to conduct this test on their patients. Another implication for clinicians is that it was shown that tablet based visual processing assessment could not identify any differences between ACLR and controls. Therefore, this form of assessment is not warranted during the rehabilitation process of ACLR athletes. Finally, an important implication for clinicians is that VR affects CoD biomechanics in ACLR athletes. Whilst further research may be required to determine if VR reduces the risk of reinjury or increases it, two subgroups of ACLR patients have now been identified (VR and NVR) who have differing biomechanical technique. Therefore, both groups may require different rehabilitation strategies. Currently, there is a lack of evidence of how to change an athlete's VR. However, if VR is detrimental to an athlete, it has been suggested the strategies such as visual distraction training and proprioceptive training may reduce VR (Grooms et al., 2015a). Visual distraction training involves the use of methods to occlude vision during a movement task so that individuals cannot rely on their visual inputs as much as before. This would help to upregulate their motor control centres to utilise more proprioceptive information. However, if NVR is detrimental to an athlete,

then strategies to encourage VR may be utilised such as internal focus during exercises and mental visualisation practice of movement tasks (Ma et al., 2022; Gokeler et al., 2019). However, with clinicians now able to more readily identify VR and NVR ACLR athletes via the stepdown task, it will help progress the exploration of the various rehabilitation techniques to determine their effectiveness in either increasing or decreasing VR.

8.2 Future research

The results of this thesis have a number of important implications. Firstly, it was able to demonstrate that ACLR VR athletes had different biomechanical technique as compared to ACLR NVR athletes during an unplanned CoD assessment. Our findings demonstrate that VR ACLR athletes employ a technique that has lower loading on the ACL as compared to ACLR NVR athletes, thereby suggesting they would have a lower ACLR reinjury risk. To determine if ACLR VR is truly protective of ACLR reinjury, a longitudinal prospective study should be completed to determine the two year and five year reinjury rates of VR and NVR ACLR athletes. This is currently planned for completion at UPMC Sports Surgery Clinic (Dublin) as ACLR athletes already currently attend the clinic approximately eight months post-surgery for 3D biomechanical testing of various movements (jumps, deceleration and CoD). It has been proposed that the stepdown test (Chapter 3) be added to the testing schedule and these athletes be followed up at two year and five years to identify who has reinjured.

A second implication from this thesis was that ACLR VR athletes may have employed a CoD movement technique that was more protective in nature due to the assessment task (lab-based unplanned CoD) not being high demanding enough on the motor planning and execution centres. The assessment task utilised in this thesis had the athlete focusing on light stimuli on two timing gates (one on the left and one on the right) to see which one activated to indicate which direction

to run towards. In normal sporting contexts, athletes are required to pick up multiple visual stimuli at any one time and make decisions or multi-task which are significantly more demanding than the task utilised in this thesis. Future research should aim to develop a reliable CoD assessment task that challenges the athletes more, potentially involving dual-task situations or increased visual attention demands, to determine if ACLR VR athletes continue to employ a more protective movement technique or if their movement technique becomes negatively affected.

A third implication of the thesis was that a stepdown task (full vision versus blinded) was able to categorise ACLR athletes as to whether they were VR or not. An athlete was classified as being VR if their time to stability during the stepdown task worsened when blinded as compared to when they had full vision (VR index score of greater than zero). The cutoff score of zero for the VR index score was arbitrarily selected as it fundamentally represented worse performance when blinded. However, without functional brain MRI or electroencephalography (EEG) (the gold standard measures for assessing VR) to confirm the amount of processing occurring within the visual centres during the stepdown task, the cutoff score of zero could be erroneous. Therefore, future research should aim to (1) recruit ACLR athletes to complete the stepdown task either whilst wearing EEG or undergoing a functional brain MRI after having completed the stepdown task to determine if a VR index score greater than zero correlates with increased processing in the visual centres of the brain, and (2) explore if a continual measure of VR provides greater understanding than a dichotomous distinction (VR versus NVR).

This thesis also demonstrated that within the ACLR population, there are two distinct groups who exhibit differing CoD biomechanics (VR and NVR). This potentially accounts for some of the mixed findings within the ACLR biomechanics literature (see Chapter 2) whereby for example some studies found peak knee valgus angle increased the risk of reinjury (Paterno et al., 2010; Hewett et al., 2005), while others did not (Pasanen et al., 2025; Ortiz et al., 2008; Di Paolo et al., 2023). Therefore, future biomechanical studies involving ACLR athletes, should examine the VR and NVR

participants separately to confirm if they exhibit differences in other movement assessments (e.g. drop jumps, drop landings etc.).

Given the differences in biomechanics between VR and NVR ACLR athletes, future studies need to determine if different methods of rehabilitation are needed for the two groups. If VR is protective in nature, then future studies should examine the effectiveness of techniques to develop VR in NVR athletes. Separately, if VR is determined to be detrimental to ACLR athletes, then future studies should examine the effectiveness of techniques to reduce VR. A study is due to commence in UPMC Sports Surgery Clinic (Dublin) to determine the effectiveness of proprioceptive and dual-task exercises in reducing VR in an ACLR cohort. It will involve two groups of ACLR participants who will perform the stepdown task to determine if they are VR. They will then complete a 12 week intervention program involving three exercise sessions per week with a supervised session every two weeks. One group will complete jumping, balance and deceleration drills with full vision, whilst the other group will complete the same exercises whilst wearing a blindfold. Following the intervention, the participants will the complete the stepdown test to determine if VR changed due to the intervention.

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Appendix A

Reliability of knee joint position sense testing utilising Vicon

The purpose of this study was to determine the reliability of a joint position sense test so that it could be utilised in a cohort study (Chapter 4) to ascertain participant's proprioception ability of the knee. The methodology has previously been reported as reliable (Relph and Herrington, 2015b) but this study will utilise different technology to measure joint angles.

A1 Introduction

Proprioception is the sense of body position that is perceived at the conscious and unconscious level (Johnson et al., 2008). Hence, it is an essential function when planning and executing movements (Moon et al., 2021). The ACL is richly innervated with proprioceptors (Dhillon et al., 2011) which provides the motor control centres with information regarding how the knee is placed in the environment. Injury to the ACL leads to a loss of the proprioceptors and can negatively affect proprioception of the knee (Dhillon et al., 2012; Anders et al., 2008; Fremerey et al., 2000)

Joint position sense (JPS) testing is a commonly used method to examine knee proprioception (Han et al., 2016; Fremerey et al., 2001; Fremerey et al., 2000). It involves participants having their knee orientated to an angle (either passively or actively) and after returning to the start

position, the participant is then tasked with moving their knee to replicate this angle. The error between the target angle and replication angle is then utilised as the measure of proprioceptive function when compared to a normative value. Previous studies have demonstrated reliable methods of measuring JPS testing of the knee such as photography, manual goniometry, electrogoniometry and utilising an isokinetic dynamometer (Relph and Herrington, 2015b; Busch et al., 2023; Jebreen et al., 2023). For example (Relph and Herrington, 2015b), demonstrated moderate-to-good reliability (ICCs 0.70 to 0.87) using photography. The photographs were then uploaded to online software, and the angle was measured utilising three points (greater trochanter, lateral femoral epicondyle and lateral malleolus) to determine the knee angle. While marker-based 3D motion capture systems, such as Vicon (Oxford Metrics, UK) have been shown to be accurate and reliable methods of measuring joint angles (Windolf et al., 2008; McGinley et al., 2009), no study to date appears to have directly examined the use of marker-based 3D systems to assess JPS.

The aim of this study was to determine the reliability of JPS testing methodology as employed by Relph and Herrington (2015) but utilising Vicon 3D motion capture. It was hypothesised that the system would allow reliable determination of JPS.

A2 Methods

Participants

A repeated measures design was utilised with participants tested five to seven days following their first testing session. 11 healthy participants (3 females, 8 males, age= 25.9 years, height= 177.4cm, weight= 79.3kg) (see Table A2) participated in the study. They were excluded if they had any current musculoskeletal, brain or neurological injuries, or if they had a previous knee injury in the preceding six months. Informed consent was obtained from all participants and was approved by the ethics and research committee of the Sports Surgery Clinic, Dublin, Ireland. A priori power analysis was conducted utilising 'Sample size calculator (web)' (Arifin, 2025). 11

participants were required when an expected ICC value of 0.9, minimum acceptable ICC value of 0.5, significance level of 0.05 and power at 80% were required.

Table A2. Participant Demographics. Mean Values Presented with Standard Deviation (SD)

	Male (SD)	**Female (SD)**	**Total (SD)**
Number of participants	8	3	11
Age (years)	26.5 (3.1)	24.3 (1.2)	25.9 (2.8)
Height (cm)	181.1 (2.5)	167.5 (0.8)	177.4 (6.7)
Weight (kg)	86.6 (5.7)	59.7 (1.5)	79.3 (13.5)

Joint position sense test

JPS testing utilised a Vicon 3D (Nexus version 2.12) assessment and an eight-camera motion analysis system (200Hz: Bonita-B10, Vicon, UK) recording 24 reflective markers (1.4cm diameter). This procedure has been previously detailed (King et al., 2018). Participants were barefoot with reflective markers secured to the skin using double-sided tape, at bony landmarks on the lower limbs, pelvis and trunk according to the plug-in-gait marker set (Marshall et al., 2014). Motion data were low-pass filtered using a fourth-order Butterworth filter (cut-off frequency of 15Hz) (Kristianslund et al., 2012).

The JPS testing protocol was adapted from Relph and colleagues (Relph and Herrington, 2016b; Relph and Herrington, 2015b) which has been shown to be reliable in uninjured controls (Relph and Herrington, 2015b). Participants were seated on a chair with their back unsupported and knees off the edge of the chair. The lateral femoral condyle was 10cm anterior to the edge of the chair to ensure that the skin around the knee, especially in the popliteal fossa, did not touch the

chair and thereby provide any extra mechanosensitive information to the patient. The participant's relaxed leg was passively extended by the examiner to an angle between 0° and 45°. The participant was instructed to actively hold this angle for five seconds and to "make a mental note of how their knee is positioned and to remember the feeling of this target angle" whilst the examiner removed their support of the leg (Figure A.2). The examiner then brought the participant's knee back to the starting position. Participants were then instructed to actively extend their knee to the position of the target angle and hold it there for five seconds. A total of five trials were collected for each leg.

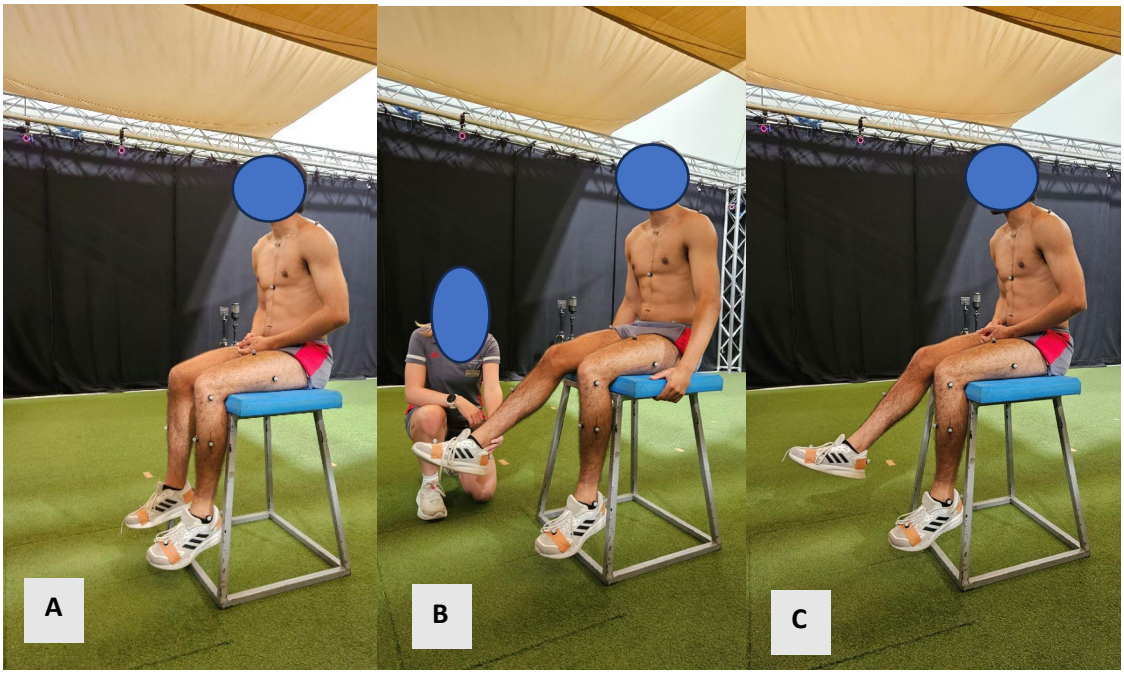


Figure A.2. Procedure for joint position test. **A** participant sitting at rest **B** Examiner extends knee to target angle **C** Examiner removes hand and participant is to maintain angle

Statisical analysis

The absolute error (AE) was recorded for each trial, which is the angular difference between the target angle set by the examiner and the angle replicated by the participant. The mean of the AE across five trials was calculated for both legs of participants. Reliability was

assessed using two-way random effects model of intraclass correlation coefficient (ICC2,1). 95% confidence intervals (CIs) were calculated for each ICC. ICCs were classified as less than 0.5 as poor, 0.5-0.75 as moderate, 0.75-0.90 as good, and greater than 0.90 as excellent (Koo and Li, 2016). Standard error of the mean (SEM) was calculated as:

$$SEM = Standard\ deviation_{pooled}\ x\ \sqrt{(1 - ICC}$$

Minimal detectable change (MDC) was calculated to allow clinicians to identify when a change is clinically different between two measurements. MDC was calculated as:

$$MDC = SEMx\ 1.96\ x\ \sqrt{2}$$

A3 Results

All participants were able to complete the task. The absolute error measure and ICC values are presented in table A3.

The dominant and non-dominant limbs demonstrated good reliability (p= 0.003, p= 0.015, respectively). The SEM for the dominant and non-dominant limbs were 1.23° and 0.88°, respectively. The minimal detectable change for the dominant and non-dominant limbs were 3.40° and 2.44°, respectively.

Table A3. Absolute error values and corresponding intraclass coefficients (ICCs), standard error of measurement (SEM) and minimal detectable change (MDC) values for both legs

	Day 1- absolute error		**Day 2- absolute error**				
	mean	**SD**	**mean**	**SD**	**ICC**	**SEM**	**MDC**
Dominant limb	3.37°	2.20	3.18°	2.94	0.86* (0.48-0.96)	1.23	3.40°
Non-dominant limb	2.58°	1.63	2.17°	1.23	0.76* (0.18-0.93)	0.88	2.44°

Abbreviations: SD= standard deviation

A4 Discussion

The aim of the study was to determine the reliability of JPS testing utilising Vicon 3D tracking system. The results of the study demonstrated good reliability for both the dominant and non-dominant limb (ICCs 0.86 and 0.76, respectively) and good precision (SEM: dominant limb= 1.23° and non-dominant limb= 0.88°, and MDC: dominant limb= 3.40° and non-dominant limb=2.44°).

The good ICC reliability noted in this study reflects the good reliability in Relph and Herrington (2015) who reported ICCs of 0.70 to 0.87 whilst utilising photography. Vicon systems are considered the gold standard for measuring 3D biomechanical analysis (Brink et al., 2013) due to having high accuracy and less than a 1.5° error (Ehara et al., 1997; Richards, 1999). The absolute error reported in this study was 3.18-3.37° for the dominant limb and 2.17-2.58° for the non-dominant limb which are also similar to values reported in Relph and Herrington (2015) (dominant limb= 1.7-2.6° and non-dominant limb= 1.9-2.9°) utilising photography. The values also were similar to those reported in a study utilising Vicon 3D motion capture in healthy controls (2.62-3.16°) (Nakashima et al., 2021).

When examining the SEM, there was similarity in this study for the non-dominant limb as compared to that reported in Relph and Herrington (2015) but there was a larger SEM in this study for the dominant limb (1.23 as compared to 0.49-0.60). This suggests there is higher variability in this study's cohort when examining their dominant limb. This potentially may be due to the smaller number of repetitions that were completed in this study (n = 5), compared to that of Relph and Herrington (2015) (n = 15) resulting in increased variability across repetitions.

A limitation of the study was that participants were only healthy individuals. Future studies would be required in the ACLR population to ensure that it is a reliable measure in that population.

A5 Conclusion

JPS testing of the knee, assessed utilising a marker-based, 3D Vicon motion analysis system with the methodology for knee extension as previously reported (Relph and Herrington, 2015b), demonstrated good reliability for both the dominant and non-dominant limb.

Appendix B

Sensorimotor dysfunction following anterior cruciate ligament injury (Part 1). What is it? How can clinicians assess it?

The purpose of this study was to summarise the available literature regarding sensorimotor dysfunction following an ACLR and how clinicians can assess all facets of the dysfunction. The study was aimed at being a practical resource to clinicians so that they could employ the techniques easily in their clinical practice.

B1 Abstract

Background

The anterior cruciate ligament (ACL) holds an important sensory role within the sensorimotor system. Following ACL injury, sensorimotor dysfunction may occur which can have implications for rehabilitation and risk of reinjury.

Clinical question

What dysfunction occurs within the sensorimotor system following ACL injury and how can clinicians assess it?

Key results

Following ACL injury, dysfunction occurs across all aspects of the sensorimotor system: afferent pathways, efferent pathways and central processing. The afferent pathways exhibit dysfunction within the somatosensory system ([1] increased pain and swelling, [2] increased central cortex

processing and [3] reduced proprioception. It also exhibits dysfunction within the visual system (increased visual-motor reliance and central cortex processing). The efferent pathways exhibit reduced excitability of the central cortex, reduced descending motor pathway excitability and altered spinal reflexive excitability (acutely reduced but then chronically increased).

Clinical application

Clinicians should develop protocols to assess their athletes following ACL injury to identify any sensorimotor dysfunction, potentially reducing the risk of reinjury. Assessment of central processing activity requires specialised equipment, not typically accessible to clinicians, therefore requiring a more practical approach to quantify the extent of sensorimotor dysfunction. Clinicians should focus on assessing the afferent and efferent pathways: tests of proprioception (e.g. joint position sense test), pain (e.g. visual analogue scale and numerical pain rating scale), swelling (e.g. sweep test and ballottement test), visual-motor reliance (e.g. stepdown test), visual-motor processing ability (e.g. sensory stations or neurocognitive tests), strength assessment (e.g. repetition maximum testing or isokinetic dynamometry) and muscular voluntary activation (e.g. electromyography assessment).

Key words

Anterior cruciate ligament, sensorimotor dysfunction, assessment, rehabilitation, afferent, efferent

B2 Introduction

Anterior cruciate ligament (ACL) injuries are common in multidirectional sport athletes with an incidence of 30-78 per 100,000 person years (Gans et al., 2018; Bollen, 2000; Nordenvall et al.,

2012). Even following an ACL reconstruction (ACLR), return to sport can take an athlete 6 to 12 months and a high risk of reinjury remains, especially for young individuals (Erickson et al., 2016; Paterno et al., 2010; Webster et al., 2019; Wiggins et al., 2016; Chia et al., 2022). 70-85% of all ACL injuries occur with a non-contact mechanism, such as sudden decelerations, change of direction and landing from a jump (Boden et al., 2000; Takahashi et al., 2019), suggesting that an athlete's movement strategy plays a significant role in ACL injury, with errors in motor planning and execution being a potential risk factor (Grooms et al., 2017; Swanik, 2015).

The sensorimotor system is complex and a central element of the body's motor control system that assists with the planning and execution of movement (Riemann and Lephart, 2002a). It encompasses the afferent sensory systems, the efferent motor pathways and the processing within the central cortex (Riemann and Lephart, 2002a). The afferent sensory systems include the following: visual, somatosensory (interpreting sensations from the skin and within the body such as pain, touch and vibration), vestibular (balance and spatial orientation), olfactory (smell), gustation (taste) and auditory (hearing) systems (Møller, 2003; Puce and Carey, 2010). The integration of sensory information from these afferent systems, especially the somatosensory and visual systems, allow the individual to gain accurate information from the environment so that an appropriate movement strategy can be employed (Figure 1). The efferent motor pathways are then utilised to carry the information to the muscles to execute the desired movement strategy.

Musculoskeletal injuries, such as ACL injuries, have been shown to lead to changes within the sensorimotor system and ultimately results in sensorimotor dysfunction (Hass et al., 2010; Grooms et al., 2017; Neto et al., 2019a; Nyland et al., 2017; Kapreli et al., 2009). This dysfunction leads to errors in movement planning and execution, resulting in the athlete employing a movement strategy which is inefficient or potentially injurious (Swanik, 2015). Recently, it has been suggested that sensorimotor dysfunction following ACLR may be a risk factor in sustaining a reinjury to the ACLR limb or injury to the contralateral limb (Grooms et al., 2015c; Swanik, 2015) even after completing rehabilitation and returning to competitive sport. Therefore, there is a need for

clinicians to understand how sensorimotor dysfunction can occur following ACL injury, how to assess the dysfunction and ultimately how to rehabilitate it.

The purpose of this clinical commentary is to outline the changes that occur within the sensorimotor system following an ACL injury and propose methods that clinicians can utilise to identify dysfunction. These methods are evidence-based suggestions that are driven by mechanistic research and clinical practice in our sports medicine facility. A follow up, part 2 clinical commentary, focuses on the evidence surrounding rehabilitation techniques that can target identified dysfunction.

B3 Clinical Question

What dysfunction occurs within the sensorimotor system following ACL injury and how can clinicians assess these? The ACL has two important roles within the knee: (1) providing structural stability through the limitation of excessive anterior translation and internal rotation of the tibia in relation to the femur primarily and knee valgus motion secondarily (Dargel et al., 2007; Shin et al., 2009), and (2) providing sensory information to the sensorimotor cortex to facilitate motor planning and execution (Gomez-Barrena et al., 1996; Park et al., 2005). Therefore, ACL injury has negative consequences for both the structural stability of the knee and the efficacy of the sensorimotor system. ACLR has been the predominant management strategy of athletes aiming to return to change of direction sports due to the high demands on both the structural and functional stability of the joint during these activities (Kannus and Järvinen, 1987; Paschos and Howell, 2017; Fithian et al., 2005). However, despite the restoration of structural stability after surgery there is a growing body of evidence that sensorimotor dysfunction remains (Grooms et al., 2015a; Grooms et al., 2017). This may negatively affect an athlete's ability to effectively gain sensorimotor information from the environment when planning a movement. Alterations in efferent motor pathways have also been noted to remain following an ACLR, even up to two years post-surgery with reduced strength and activation of the quadriceps (Hart et al., 2010; Herrington et al., 2021). The failure to

resolve sensorimotor dysfunction may reflect that clinicians currently lack the clinical tools to either identify individuals with sensorimotor dysfunction or that rehabilitation methods are inadequate. The following sections outline the components of the sensorimotor system (afferent and efferent), methods to assess their function in clinic, and deficits reported after ACLR. Dysfunction in the sensorimotor system following ACLR is thought to be the same as that occurs with ACL injuries that are managed non-operatively and therefore in this clinical commentary, the two conditions (ACLR and ACL injuries) are not separated.

B4 How does sensorimotor dysfunction impact movements?

Motor planning and execution is complex, with the need to coordinate numerous muscles and joints to complete the desired movement task. Neurocognitive demands (the processing of sensory, motor, emotional and higher executive information in the central cortex) are increased when motor planning and execution is performed in a sporting situation due to higher speed of movement, greater decision-making complexity and reduced decision-making time. It has been suggested that an athlete's movement strategy is determined by their constraints (anthropometrics and physical capacities such as strength and power), the information they perceived from the environment (position and movement of opponents) and the constraints placed by the task (e.g. attempting to score a goal) (Davids et al., 2012; Araújo et al., 2013; Wade and Whiting, 1986). The interaction between perception of the environment and subsequent action continuously occurs (Gibson, 1986), requiring the integration of sensory information to gain accurate information from the environment so that an appropriate movement strategy can be employed (Figure B4). Individuals have several sensory systems: visual, somatosensory (interpreting sensations from the skin and within the body such as pain, touch and vibration), vestibular (balance and spatial orientation), olfactory (smell), gustation (taste) and auditory (hearing) (Møller, 2003; Puce and Carey, 2010), with the somatosensory and visual systems being the most pertinent for motor planning and execution.

Therefore, sensorimotor dysfunction can lead to increased neurocognitive demands or a reduced ability to plan high impact movements efficiently (such as cutting or jumping/landing), resulting in the selection of non-optimal movement strategies that may increase the risk of injury and reduce athletic performance post ACLR.

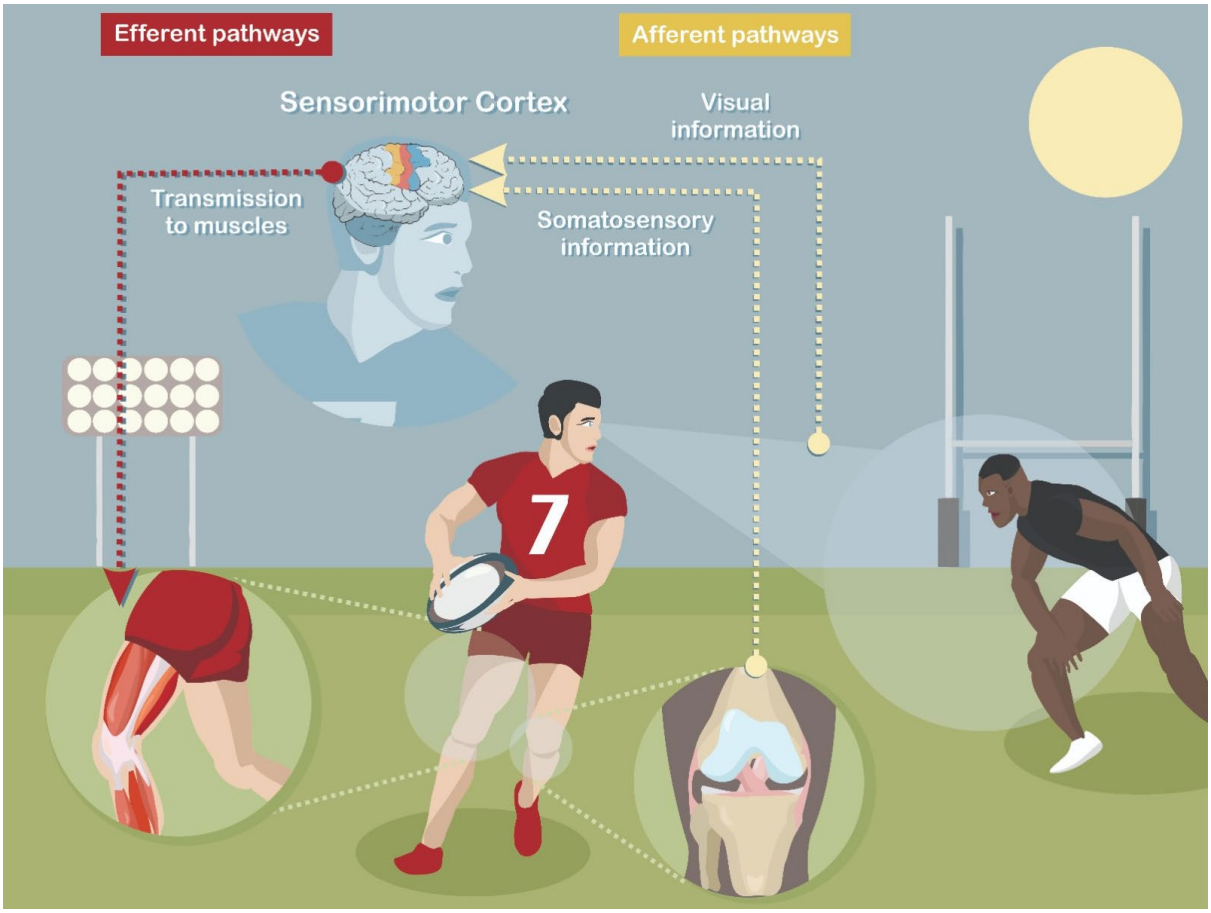


Figure B4. An individual utilises somatosensory and visual systems to attain information to help the sensorimotor cortex create an appropriate motor response.

B5 Key results

Afferent System

Somatosensory system

The somatosensory system has several functions including: (1) informing the central cortex about the position and movement of segments of the body (proprioception) and, (2) sensing painful

and pressure/vibration stimuli (Puce and Carey, 2010). Proprioception utilises fast velocity proprioceptor afferent fibres within the soft tissues (muscle, ligament and joint tissue) to provide the sensorimotor cortex with information regarding the starting posture of the body so that appropriate coordination of motor units can be produced to execute a movement (Proske and Gandevia, 2012). The second somatosensory function utilises pain and pressure receptors within the soft tissues to detect pain or swelling so that if an injury occurs or tissue damage may be imminent, then the body can coordinate a motor response to minimise the damage or protect the injured structure (Rice and McNair, 2010; Sandrini et al., 2005).

A full-thickness tear of the ACL results in a complete loss of its numerous mechanoreceptors (Dhillon et al., 2012). One of the goals after ACLR is to regain proprioceptive function by providing a graft that becomes the scaffolding for new afferent nerve fibres to grow into (Dhillon et al., 2011). However, the return of these mechanoreceptors following ACLR is quite often slow and variable.(Dhillon et al., 2012) The variable return of mechanoreceptors (3-6 months post-surgery) may lead to altered somatosensory processing and a reorganisation of the sensorimotor cortex with greater reliance being placed on the visual system (Neto et al., 2019a). Knee proprioception has been shown to be significantly reduced in the ACLR limb after surgery, compared to both the uninjured limb and healthy control limbs, even after individuals had completed rehabilitation and returned to sport (Lehmann et al., 2017; Relph and Herrington, 2016b; Relph et al., 2014a). There is some evidence that changes in surgical technique to preserve the remnants of the ACL during reconstructive surgery may lead to improved proprioception (Cho et al., 2022) in athletes as compared to a more standard ACLR but this surgical technique is not commonly completed. The diminished proprioceptive ability amongst athletes following ACLR may result in greater error for the individual when determining how their body is positioned in the environment and thereby lead to non-optimal movement strategies being employed. Therefore, a clinician's ability to measure proprioception in their athletes following ACL injury or ACLR may be critical.

Pain and swelling following an ACL injury is thought to have a strong role in the inhibition of quadriceps activation (Rice and McNair, 2010). Swelling within the knee joint (effusion) causes activation of afferent pressure receptors within the joint capsule (Nyland et al., 1994) due to high intra-articular pressures, and chemical activation of the receptors due to inflammatory cytokines (Rice and McNair, 2010). Activation of the afferent pressure receptors can result in significant reductions in quadriceps activity (Palmieri-Smith et al., 2007) and strength (McNair et al., 1996). Similarly, pain and inflammation is thought to sensitise afferent receptors within the joint capsule and connective tissues, leading to further inhibition of the quadriceps (Rice and McNair, 2010; Nyland et al., 1994), with strength losses of 80-90% within the first few days following knee surgery, which may persist in the weeks after (Shakespeare et al., 1985). It is therefore essential that clinicians measure and monitor an athlete's pain and effusion throughout the rehabilitation process following an ACL injury or ACLR.

Assessment

Assessment of somatosensory function following ACLR in the literature takes several forms: assessing processing demands in the somatosensory cortex, assessing proprioception, and assessing pain and effusion (Table B5.1). However, many of the assessments for processing demands in the somatosensory cortex require technology (e.g. functional brain MRI) that is not easily accessible for clinicians or require specialist training. Therefore, clinicians should focus on assessments of proprioception, pain and effusion as their measures of afferent somatosensory function.

Proprioception

A difficulty with examining proprioceptive function is that it covers several domains: (1) awareness of position of body segment (joint position sense), (2) sense of movement (kinaesthesia), (3) sense of velocity of movement, and (4) the ability to sense force and thereby reproduce a set

level of force (Proske and Gandevia, 2012). Many of the methods used to examine these (especially kinaesthesia, sense of velocity, sense of force) utilise specialised tools, such as isokinetic dynamometers, which may not be accessible to most clinicians. Joint position sense (JPS) testing, on the other hand, can be conducted via a number of methods which are easily accessible for clinicians and have previously been used to demonstrate significant proprioceptive impairment in the ACLR limb when compared to the uninjured limb and/or the limbs of uninjured participants (Relph et al., 2014a; Gokeler et al., 2012). Therefore, we would suggest clinicians use JPS testing in their clinical practice to assess proprioceptive function following an ACLR.

1

Table B5.1. Tests of somatosensory function

Somatosensory domain	Clinical test	Use	Equipment needed	Facilitators	Barriers
Somatosensory cortical processing	Functional brain MRI	Allows clinicians to determine if altered processing is occurring in somatosensory cortical areas during a movement task (eg. Knee flexion and extension)	MRI machine and specialist software	Able to identify areas of brain active during movement	Financial and time cost. Expertise to interpret the scan.
	Electroencephalogram	Allows clinicians to determine if altered processing is occurring in somatosensory cortical areas during a movement task (eg. Knee flexion and extension)	EEG device and specialist software	Able to identify areas of brain active during movement	Financial and time cost. Expertise to interpret the scan.
Proprioception	Joint position sense tests	Whilst their vision is obstructed, athletes have their knee moved to an angle by the assessor and the athlete is then asked to move the knee to replicate the angle	Isokinetic dynamometer	Reliable measurement	Cost of equipment

			Camera and angle calculator software	Easy to set up and reliable measurement	Can take time to setup, process images and measure angles
			Digital goniometer	Easy to set up and reliable measurement	
	Threshold to detect passive motion	Whilst their vision is obstructed, the athlete is instructed to report when they feel their knee move.	Isokinetic dynamometer	Reliable measurement	High cost
	Ability to detect change in velocity	Whilst their vision is obstructed, the athlete reports to the assessor when they feel the speed of their knee movement changes	Isokinetic dynamometer	Reliable measurement	High cost
	Force reproduction tests	The athlete completes an isometric contraction in an attempt to hit a target threshold (generally 50% of maximum voluntary contraction).	Isokinetic dynamometer	Reliable measurement	High cost
Pain	Visual Analogue Scale (VAS)	The athlete rates the magnitude of their knee pain by making a mark on a 10cm line (0= no pain and 10= worst pain imaginable)	Paper and ruler	Quick and reliable measurement	The assessment is very subjective so can vary due to non-physical factors
	Numerical Pain Rating Scale (NPRS)	The athlete rates the magnitude of their knee pain from 0 to 10 (0= no pain and 10= worst pain imaginable)	Nil equipment	Quick and reliable measurement	The assessment is very subjective so can vary due to non-physical factors

Effusion	Sweep test	Assessor uses sweeping motion around the knee to measure the effusion.	Nil equipment	Quick and simple test	Inter-observer reliability can be varied
	Patellar Ballottement test	Assessor applies pressure to the knee and assesses the degree to which the patella floats to determine level of effusion	Nil equipment	Quick and simple test	Inter-observer reliability can be varied

2

JPS testing assesses how well an athlete can identify when their knee has been moved (actively or passively, depending on protocol) to an angle that replicated a target angle that they were previously positioned at by the assessor. JPS testing can be split into three broad categories: image recorded angulation testing (a photograph is taken of the limb and the examiner measures the angle), electrogoniometry (use of digital goniometers to measure the angle) and isokinetic dynamometry (use of isokinetic dynamometer to measure the angle). Whilst all three categories of testing have been shown to be reliable (Nobori et al., 2004; Piriyaprasarth et al., 2008; Ghiasi and Akbari, 2007; Relph and Herrington, 2015b), clinicians should be cognisant of the exact protocol they choose as some published JPS protocols have poor reliability (Smith et al., 2013). The absolute error (difference between target angle and athlete's angle replication attempt) is taken for each trial and a JPS deficit is indicated by a greater difference in absolute error score between limbs. An image-recorded angulation JPS testing method that can be implemented in the clinic quite easily and has demonstrated good reliability (ICC=0.96-0.98) can be found in Appendix A (Relph and Herrington, 2016b; Relph and Herrington, 2015b; Relph and Herrington, 2015a). Within a population of ten ACLR elites athletes, they demonstrated a difference of 5.3° in absolute error between the ACLR limb (absolute error= 7.2°) and the uninjured limb (absolute error= 1.9°) as representative of proprioceptive dysfunction in the ACLR limb (Relph and Herrington, 2016b). Therefore, if an interlimb difference of ≥5.3° is found by clinicians, then it may suggest that proprioceptive training be prescribed to their athlete. We would suggest that JPS testing be completed every four to six weeks during rehabilitation until no deficit is detected.

Assessing pain and swelling

Regularly assessing pain and swelling following an ACL injury is essential for a clinician to minimise any potential muscle inhibition, in particular quadriceps and hamstrings (McPherson et al., 2023), and to ensure that the athlete's knee is tolerating progression through the rehabilitation program. When measuring pain, the two most common methods are the numerical rating scale and

the visual analogue scale. Both methods have been shown to be valid and reliable so selecting a method is based on what the athlete prefers (Thong et al., 2018). The numerical rating scale has the athlete reporting their pain on a scale of 0-10 with “0” being no pain and “10” being the worst pain they could imagine. A minimal clinically important change has not been examined in the ACLR population but it has been suggested to be 2 points in those with chronic musculoskeletal pain (Salaffi et al., 2004). The visual analogue scale is different in that patients are required to mark their pain on a 10-centimetre line with ‘0’ being no pain and ’10 centimetres’ being the worst pain they could imagine. A minimal clinically important change has not been established for the ACLR population but it has been suggested to be 1.4 centimetres for musculoskeletal conditions and chronic pain (Delgado et al., 2018; Joyce et al., 1975). Therefore, if athletes continue to have pain during rehabilitation and are not showing improvements, then strategies surrounding pain management should be discussed with the athlete and physician. This is particularly important during the early stage of rehabilitation as pain may negatively affect an athlete’s ability to recruit their muscles (Henriksen et al., 2011) and may also lead to limb off-loading strategies. Also, during the mid-to-late stages of rehabilitation, pain that is negatively affecting how well the athlete can execute their sporting motor tasks or their rehabilitation exercises needs to be addressed. Pain assessments should be completed every session the athlete has with the clinician until the pain resolves to allow for clinicians to see how the athlete is responding to their interventions.

Measurement of swelling following ACL injury is not a direct measure of afferent function but rather it allows clinicians to assess a secondary factor (pressure or inflammation) which may be inhibiting mechanoreceptors within and surrounding the knee. Measuring knee effusion is done clinically via the sweep test or the ballottement test which both have good inter-observer agreement (Cibere et al., 2004). The sweep test is performed with the knee in extension and the clinician sweeping their hand firmly distal to proximal along the medial edge of the knee. A broad and firm sweep is then made along the lateral aspect of the knee (distal to proximal) whilst observing for any fluid return to the medial aspect of the knee. The sweep test is graded on a scale from 0 to 3+ (see appendix

video). The ballottement test is performed with firm downward and distal pressure being applied to the suprapatellar pouch with one of the clinician's hands. The clinician then uses their other hand to firmly push down on the patellar, towards the femur. If an effusion is present, then the patellar will wave or have a spongy feel as compared to the contralateral knee. The ballottement test is graded on a scale from I to IV (see appendix video). Athletes who have more than trace effusion on the sweep test or more than a grade I on ballottement testing are flagged and methods to manage the effusion are put in place, such as reducing training loads, passive modalities or medication. If an effusion is failing to settle, then the athlete may be referred for radiological investigation to assess if there is an intra-articular pathology source for the effusion. A video on how to complete the sweep and ballottement tests can be found in Appendix B. Effusion testing should be completed at every session the athlete has with the clinician until it has resolved to ensure that the knee is responding appropriately to the interventions.

Visual system

The visual system encompasses the eyes, optical neural pathways and the occipital lobe (where processing of the visual information occurs). It has been suggested that the visual system may be the predominant sensory system utilised during planning and execution of motor tasks (Goodale, 1998; Duchowski, 2017; Stein and Glickstein, 1992), such that when there is conflict between afferent information provided by the somatosensory system and that of the visual system, then the visual information will take precedence when planning a motor response (Stein and Glickstein, 1992; Patla, 1997). While there are a number of theories as to how the visual information is processed and interpreted, the common thread between them is that the information from the visual system provides the central cortex with information regarding what is in the environment and where it is positioned (Duchowski, 2017).

There is currently limited research examining the changes that occur to the visual system and changes in how visual information is processed following ACL injury. Of the available literature, the term visual-motor system is utilised to encompass all of the visual processes and how they influence motor actions (Burris et al., 2020; Goodale, 1998; Grooms et al., 2018; Grooms et al., 2015a). Functional brain MRI studies have shown increased activity in the visual processing cortices following ACLR (Nyland et al., 2017; Grooms et al., 2017). It has been theorised that the increased visual processing activity stems from the loss of proprioception during the ACL injury and the subsequent effusion and nociception (Grooms et al., 2015a). The altered afferent information from the knee to the sensorimotor cortex leads to a reduction in postural control, and increased demands placed on motor planning centres in the frontal lobe and secondary somatosensory cortices (as evidenced by functional brain MRI) (Grooms et al., 2017; Neto et al., 2019a). To manage the reduced postural control and afferent input from the knee, a re-weighting of the sensory systems may occur with an increased reliance placed on visual information during motor planning and execution (Grooms et al., 2017). This re-weighting potentially contributes to an increased cognitive demand during motor activities which may be detrimental to an athlete by reducing their ability to react quickly to their changing environment. Given the potential link between increased reliance on the visual-motor system and ACLR reinjury (Grooms et al., 2015c), it is important that clinicians can assess their athletes for potential increased visual reliance.

Assessment

Assessment of visual function in the literature commonly covers two domains: assessing visual-motor processing ability and assessing for increased reliance on the visual-motor system via balance tests (see Table B5.2 for list of tests).

Visual-motor processing ability

Visual-motor processing ability encompasses all of the processes that occur from an athlete using their eyes to capture information of the environment, the processing of the visual information in the central cortex and then its influence on motor execution. Poor visual-motor processing ability (visual memory, reaction time and processing speed) may play a role in non-contact ACL injuries when tested with the ImPACT computer-based neurocognitive test (ImPACT Applications Inc.) (Swanik et al., 2007).

Assessing visual-motor processing ability in athletes can be completed via a computer-based neurocognitive test which are commonly used for concussion assessments. There are many different companies (e.g. ImPACT [https://impacttest.com/], and Cogstate [https://www.cogstate.com/]) providing the tests and they are easy for clinicians to administer at a relatively low cost, even on a large scale. These neurocognitive tests have been demonstrated to be reliable in uninjured athletes (Netzel et al., 2022) but no study to date has examined their reliability in the ACLR population. A common issue with the neurocognitive tests utilised for concussion is that they predominantly test memory and speed of processing domains, with a lack of varied visual-motor domains.

The advent of 'sensory stations' and tablet systems (such as the system offered by Senaptec, Oregon USA) with visual-motor specific testing has meant that clinicians can more easily assess athletes across a number of visual-motor domains which reflect abilities that athletes require to effectively pick up cues from the environment, such as visual acuity (ability to discern shapes and details of objects), visual memory (ability to store visual information so that learning can occur from previous experiences), near-far eye movements (ability to switch gaze from near to far objects) and multiple object tracking ability (allowing an athlete to pick up multiple cues in the environment)(a video which encompasses the nature of the tests can be found at https://www.youtube.com/watch?v=4Vj78RX7oVo). This device has been shown to have good reliability in uninjured athletes (Erickson et al., 2011), but no studies have examined its reliability

in the ACLR population . Whilst measures of visual-motor performance on these systems have recently been found to predict in-game performances in sports such as professional baseball (Liu et al., 2020; Laby et al., 2019), there is currently no research examining ACL injury risk or changes in visual-motor function following injury utilising the sensory stations. As such, there is limited information on what a good baseline score is for each of the visual-motor domains. A further limitation is, for the tests to be beneficial for clinician's managing an athlete post ACL injury or ACLR, the athlete's baseline information would be required to determine if their function has been negatively affected by the injury. We have found athletes enjoy engaging in the sensory station due to the novelty and the varied challenging tasks. Their results can be exported as raw score to clinicians so that deeper analysis can be conducted, but the athlete is provided with an immediate percentile score (against other athletes from similar sports) which drives competition and engagement.

1

Table B5.2. Tests of visual-motor function

Visual assessments	Clinical test	Use	Equipment needed	Facilitators	Barriers
Visual cortical activity	Functional brain MRI	Allows clinicians to determine if altered processing is occurring in visual cortical areas during a movement task (eg. Knee flexion and extension)	MRI machine and specialist software	Able to identify areas of brain active during movement	Financial and time cost. Expertise to interpret the scan.
	Electroencephalogram	Allows clinicians to determine if altered processing is occurring in visual cortical areas during a movement task (eg. Knee flexion and extension)	EEG device and specialist software	Able to identify areas of brain active during movement	Financial and time cost Expertise to interpret the scan
Visual-motor processing	Neurocognitive tests (e.g. ImPACT, Cogstate)	Assesses domains such as: visual processing speed, reaction time and visual memory	Computer based test	Standardised testing procedure that	Each testing session has a cost. Assesses a limited number of visual-motor processing domains.

	Sensory stations (e.g. Senaptec)	Assesses domains such as: visual acuity, depth perception, near-far eye movement, contrast sensitivity, visual memory and multiple object tracking	Computer/tablet based test	Is easy to administer to patients. Assesses across visual-motor processing abilities that may be relevant to athletes	Cost of device can be high. Needs further research in ACLR population
Visual-motor reliance	Single leg balance. Eyes open versus eyes closed	To assess postural control differences between eyes open and eyes closed conditions during a single leg balance task	Force plate is optional	Can use time holding the position or counting errors within specific time period as measure of postural control. Can use centre of pressure data if there is access to force plates.	Does not appear to be a good discriminator between ACLR and uninjured individuals in determining visual-motor reliance. If utilising force plates, then there is a cost.
	Stepdown test. Eyes open versus eyes closed	Measures time to stability during a stepdown task whilst are eyes open and then eyes closed. Able to then derive an index score of how visually-motor reliant an athlete may be	Force plate and step	Quick test and safe test to complete	Requires force plates to complete the test.

2

Assessing visual-motor reliance via balance tests

Balance tests are commonly conducted in clinical settings to assess an athlete's ability to integrate sensory (somatosensory, visual and vestibular) information. To effectively determine if an athlete has an increased reliance on the visual-motor system to maintain balance, the athlete should perform a task that compares their balance under two conditions: eyes open versus eyes closed. A greater deficit in performance between eyes open and eyes closed as compared to either normative data or the uninjured limb would suggest there is an increased reliance on the visual-motor system.

The most used clinical test involves a single leg balance task in which the athlete stands on one leg with their eyes open and then with their eyes closed. A comparison of their postural control can then be used to determine if there was a difference in visual-motor reliance between limbs. A review demonstrated that postural control significantly worsened when vision was obstructed in ACL deficient individuals as compared to healthy participants (Wikstrom et al., 2017). However, the ACLR population exhibit similar reductions in postural control performance as healthy participants (ACLR 42.9% reduction vs controls 44.7% reduction) (Wikstrom et al., 2017), suggesting that either: (1) visual-motor reliance does not negatively affect an ACLR athlete's ability to maintain postural control in comparison to healthy controls, or (2) the task of quasi-static standing on one leg may not be challenging enough for the sensorimotor system to identify those who may be visually-motor reliant.

A balance task that is more demanding than stationary single-leg standing may be better able to assess if an athlete is reliant on their visual-motor system. In our practice we have adapted a stepdown task (initially used by Colby and colleagues) (Colby et al., 1999) in which athletes step off a 20 centimetre height and onto a force plate where they must attain stability as quickly as possible (see Appendix C for testing methodology). Athletes complete this first with their eyes open and

then eyes closed, with time to stability used as the outcome measure (Colby et al., 1999; Byrne et al., 2021). We found this to have good reliability (ICCs= 0.71-0.96) (unpublished) and a visual-motor reliance index score can be ascribed to athletes. We are currently conducting research using this test within the ACLR population. However, amongst healthy controls, our early findings demonstrated that this population group actually improved their time to stability time by 17% when their eyes were closed. Therefore, if an athlete's time to stability worsens when their eyes closed, then we may be able to say that they are reliant on the visual-motor system and would benefit from rehabilitation strategies that would target this. If clinicians do not have access to force plates to conduct this test, subjective assessment of postural control (assessing frontal plane control of body segments such as trunk sway, hip movement, knee adduction, and foot pronation and supination) may be used to assess athlete performance when their eyes are open and then closed. In our current clinical practice, we aim to reassess visual-motor reliance every six weeks to determine if the interventions being implemented are having a positive impact on the athlete.

Efferent system

The main components of the efferent system involved in motor planning and execution are the motor cortex (in the brain), descending motor pathway (in the spinal cord) and spinal-reflexive pathways (between the spinal cord and motor unit) (Pietrosimone et al., 2012; Williams et al., 2001). Injury to the ACL has been shown to lead to changes in all three components (Pietrosimone et al., 2015b), which are still evident 6 months following ACLR (Lepley et al., 2015), manifesting in changes in muscle activation, coordination (Nematollahi et al., 2016) and reduced muscle strength (Lepley et al., 2014). This likely contributes (along with muscle atrophy) to persistent quadriceps weakness (Palmieri-Smith and Thomas, 2009; Pietrosimone et al., 2012) and ongoing dysfunction following ACLR (Logerstedt et al., 2013; Pietrosimone et al., 2013). Following ACLR, unilateral and bilateral reductions in voluntary activation of the quadriceps have been demonstrated up to four years post-surgery (Pietrosimone et al., 2015b; Lisee et al., 2019). Deficits in voluntary activation of the quadriceps can result in reductions in strength, performance (Lohmander et al., 2004) and

increased risk of reinjury (Paterno et al., 2010). Although there is some debate (Pietrosimone et al., 2015b), the driver of the strength deficit has been suggested to be the result of: (1) alterations to the three components of the efferent system (motor cortex, descending motor pathway and spinal-reflexive pathways), (2) local muscle changes such as atrophy, and (3) the negative influences from changes in the sensory system (as previously discussed). Therefore, clinicians should have a good understanding of the dysfunction that occurs within each efferent system component so that they can employ appropriate rehabilitation strategies.

Motor cortex

The motor cortex covers a number regions of the brain (e.g. premotor cortex and primary motor cortex) which are involved in the planning and initiation of voluntary movements (Li et al., 2015). Following an ACLR, it has been demonstrated that there is increased intracortical inhibition which is associated with reduced voluntary quadriceps activation in the injured limb (Luc-Harkey et al., 2017), and can occur bilaterally (Zarzycki et al., 2018). Therefore, the athlete needs to dedicate greater neural resources and effort to activate a muscle and execute a movement, as compared to preinjury, thereby potentially resulting in non-optimal movement strategies.

Descending motor pathway

The descending motor pathway refers to the corticospinal tract which carries impulses from the motor cortex through the spinal cord so that it may synapse with the lower motor neurone that activates the target muscle (Rong et al., 2014; Jang, 2014). Excitability within the descending motor pathway is reduced following ACLR via an increase in the threshold required to fire the motor neurones (via measurement of active motor thresholds) (Lepley et al., 2015; Pietrosimone et al., 2015b) which may occur in response to increased motor cortex inhibition (Groppa et al., 2012; Lepley et al., 2015). The increase in active motor threshold is associated with a reduction in

voluntary activation of the quadriceps (Pietrosimone et al., 2015b) and may result in altered movement strategies.

Spinal Reflexive pathways and peripheral changes

Spinal reflexive pathways allow for fast motor responses in response to peripheral stimuli. The ACL has a number of spinal reflexive pathways with various purposes. ACL injury and ACLR lead to pain, knee joint effusion and loss of proprioceptors within the native ACL (Palmieri et al., 2004), which results in inhibition of the quadriceps and increases motor activity within the hamstrings (Sherman et al., 2021; Hopkins et al., 2001). This results in a reduction in the athlete's ability to recruit motor units within the quadriceps to produce force, thus potentially influencing movement strategy and joint loading (Konishi et al., 2002; Konishi et al., 2003). As time progresses, the excitability of the spinal reflexive pathway to the quadriceps increases such that it is significantly greater in both the ACLR limb and unreconstructed limb in comparison to healthy athletes (Rodriguez et al., 2020; Tayfur et al., 2021) which may be a compensation by the motor system to improve quadriceps activity in response to depressed quadriceps voluntary activation (Tayfur et al., 2021) and reduced excitability of the descending motor pathway.

In summary, all components of the efferent system (motor cortex, descending motor pathway and spinal reflexive pathways) are influenced by an ACL injury. An initial reduction in excitability occurs within the spinal reflexive pathways and motor cortex. Reductions in descending motor pathway volume and excitability can then develop, with evidenced changes occurring three to six months post ACLR (Lepley et al., 2020). These factors may culminate in reduced voluntary activation and function of the quadriceps (Pietrosimone et al., 2015b), which can have a negative impact on the athlete's ability to regain strength and control around the knee during rehabilitation.

Assessment

Assessing the sub-sections of the efferent system is primarily conducted with specialised testing equipment and expertise which most clinicians will not have access to. These include Hoffman reflex to assess spinal reflexive changes, transcranial magnetic stimulation to determine corticospinal excitability, and central activation ratio to measure voluntary activation levels of muscles (details on testing methodology can be found in Lepley and colleagues, 2015) (Lepley et al., 2015). Therefore, clinicians should measure muscle strength and activation (especially the quadriceps) to determine efferent function following ACLR. Clinicians need to be aware that these tests are not able to differentiate which component of the efferent system is dysfunctional, so management strategies should be generalised to improving overall efferent function (see table B5.3 for tests of efferent function).

Table B5.3. Tests of efferent function

Efferent function	Clinical test	Uses	Equipment needed	Facilitators	Barriers
Strength assessment	Isokinetic dynamometry	Able to assess concentric or eccentric strength of quadriceps and hamstrings through a specified range of motion	Isokinetic dynamometer	Reliable measurement. Able to assess strength through a specified range of motion.	High cost
	Repetition maximum testing	Able to assess an athlete's ability to perform a movement under increasing load to determine a 1,3 or 5 repetition maximum	Gym equipment	Test can be independently completed by the athlete. Can test several movement patterns.	Can take time to complete the test when allowing for appropriate warm up and rest in between sets. If using a compound exercise for the testing protocol, then this may allow for compensatory movements to hide weakness in a specific muscle.

	Isometric strength testing	Able to assess isometric strength by fixing a handheld dynamometer with non-elastic bands to an anchored limb	Handheld dynamometer and non-elastic bands	Provides reliable measure of isometric strength	Can miss range-specific strength asymmetries
Voluntary activation	Central activation ratio	To assess the ability of an athlete to recruit their muscle. Maximum voluntary contraction is completed and output is measured. A superimposed electrical burst is then used to contract the muscle to get a maximum output. A percentage score can then be derived based off how well athlete can contract muscle in relation to maximum output available	Isokinetic dynamometer and electrical stimulation device	A reliable measure of how well an individual can recruit a muscle	Cost of equipment is high and expertise is needed to conduct the test
	Surface EMG	Allows clinicians to determine how well an athlete can recruit a muscle in comparison to the contralateral muscle during a maximum voluntary contraction	Surface EMG device	Easy to use and more accessible for individuals	Cost of equipment can be high.
Motor cortical activity	Functional brain MRI	Allows clinicians to determine if altered processing is occurring in the motor cortex during a movement task (eg. Knee flexion and extension)	MRI machine and specialist software	Able to identify areas of brain active during movement	Financial and time cost. Expertise to interpret the scan.

	Electroencephalogram	Allows clinicians to determine if altered processing is occurring in motor cortex during a movement task (eg. Knee flexion and extension)	EEG device and specialist software	Able to identify areas of brain active during movement	Financial and time cost Expertise to interpret the scan
	Transcranial magnetic stimulation	Allows clinicians to determine the excitability of the motor cortex via the application of pulses	Transcranial magnetic stimulation device, cortical mapping software, EMG and sometimes EEG	Able to identify excitability of motor cortex	Financial and time cost. Expertise to interpret the results
Descending motor pathway	Transcranial magnetic stimulation	Allows clinicians to determine the excitability of the descending motor pathway via the application of pulses to the motor neurones and measuring motor-evoked potentials in the target muscles	Transcranial magnetic stimulation device, cortical mapping software, EMG and sometimes EEG	Able to identify excitability of descending motor pathway	Financial and time cost. Expertise to interpret the results
Spinal reflex	Hoffmans reflex	Allows clinicians to measure the excitability of the spinal reflexive pathway	EMG, isokinetic dynamometer and electrical muscle stimulator	Accurate assessment of spinal reflexive excitability	Financial and time cost. Expertise to interpret the results

Evaluation of quadriceps and hamstrings strength can be conducted via repetition maximum testing (1, 3 or 5 repetition maximum), handheld dynamometry or isokinetic dynamometry. Although used in the literature interchangeably as part of strength assessments, they do not provide equivalent measures of strength following a strengthening program (Gentil et al., 2017). Repetition maximum testing appears to be best placed to examine strength changes through a specific movement such as squats, knee extensions or deadlifts (Gentil et al., 2017) which may be of benefit for clinicians to examine if functional patterns in their athletes are improving. However, a limitation of using repetition maximum strength testing is that multi-joint movements such as squats may demonstrate improvements due to improved inter-segmental coordination, which may mask any lack of improvement in isolated quadriceps strength. Isokinetic dynamometry is the gold standard for examining the transfer of strength to muscle groups following a training program (Drouin et al., 2004; Gentil et al., 2017). It can assess the torque produced around a single joint through a given range of motion and is therefore best placed to assess isolated quadriceps and hamstrings peak torque. Isokinetic dynamometry has high reliability (ICC= 0.74 – 0.93) (Sole et al., 2007; Habets et al., 2018) when assessing quadriceps and hamstrings peak torque. Normative data suggests that elite male field-based athletes should be achieving a quadriceps peak torque of 3.19 ± 0.1 Nm/kg and 1.78 ± 0.1 Nm/kg, whilst elite female field-based athletes should achieve a quadriceps peak torque of 2.32 ± 0.36 Nm/kg and hamstrings peak torque of 1.36 ± 0.21Nm/kg (van Melick et al., 2022). Using these values as benchmarks for our multi-directional field sport athletes, athletes falling below these levels would be prescribed strategies to improve strength and efferent function. A standardised protocol for assessing ACLR athletes was recommended following review (Undheim et al., 2015) and has been described in Appendix D. Although access to isokinetic dynamometry is improving, it may still be out of reach for many clinicians. Handheld dynamometry can be a cost-

effective alternative for clinicians to examine quadriceps strength. It has been shown to be reliable and valid in measuring isometric quadriceps strength when utilising non-elastic straps (Lesnak et al., 2019; Almeida et al., 2019). The disadvantage of handheld dynamometry as compared to isokinetic dynamometry is that it is not able to identify range-specific strength deficits (Hart et al., 2022). Strength assessments should be completed every six to eight weeks to ensure the athlete is responding to the interventions set out by the clinician.

Deficits in voluntary activation of the quadriceps have been shown to persist following ACLR (Lisee et al., 2019). Surface EMG biofeedback devices are easily accessible to clinicians and can determine the magnitude of motor unit recruitment during a contraction, which can give insight into any potential altered efferent function. Recently, commercially available surface EMG biofeedback units (e.g. 'mTrigger', LLC, *Delaware, USA,* and Neurotrac Myo Plus 2, *Verity Medical Ltd*) have reported that they can compare EMG activity between limbs via dual-channel EMG. The athlete performs three to six repetitions (the number will vary between devices) of maximal isometric quadriceps activation on the injured limb and the healthy limb, with the surface electrodes placed over the motor points of the quadriceps. The difference in EMG activity between the two limbs is compared to observe for any large differences (a 22%-30% difference between limbs may be significant) (Pamukoff et al., 2017; Cui et al., 2023) and can guide clinicians to implement appropriate strategies to improve efferent function (Buckthorpe et al., 2019; Sonnery-Cottet et al., 2019). Appendix E details a method of utilising the technology to assess for any reductions in voluntary quadriceps activation. We would suggest that assessment of voluntary activation be completed every two weeks until no significant difference is noted between the limbs.

B6 Summary and Implications

ACL injury and ACLR are both significant events for an athlete which causes sensorimotor dysfunction. The changes that occur to the sensorimotor system following an ACLR and where the assessments fit into clinical practice can be summarised by the following (Figure B6):

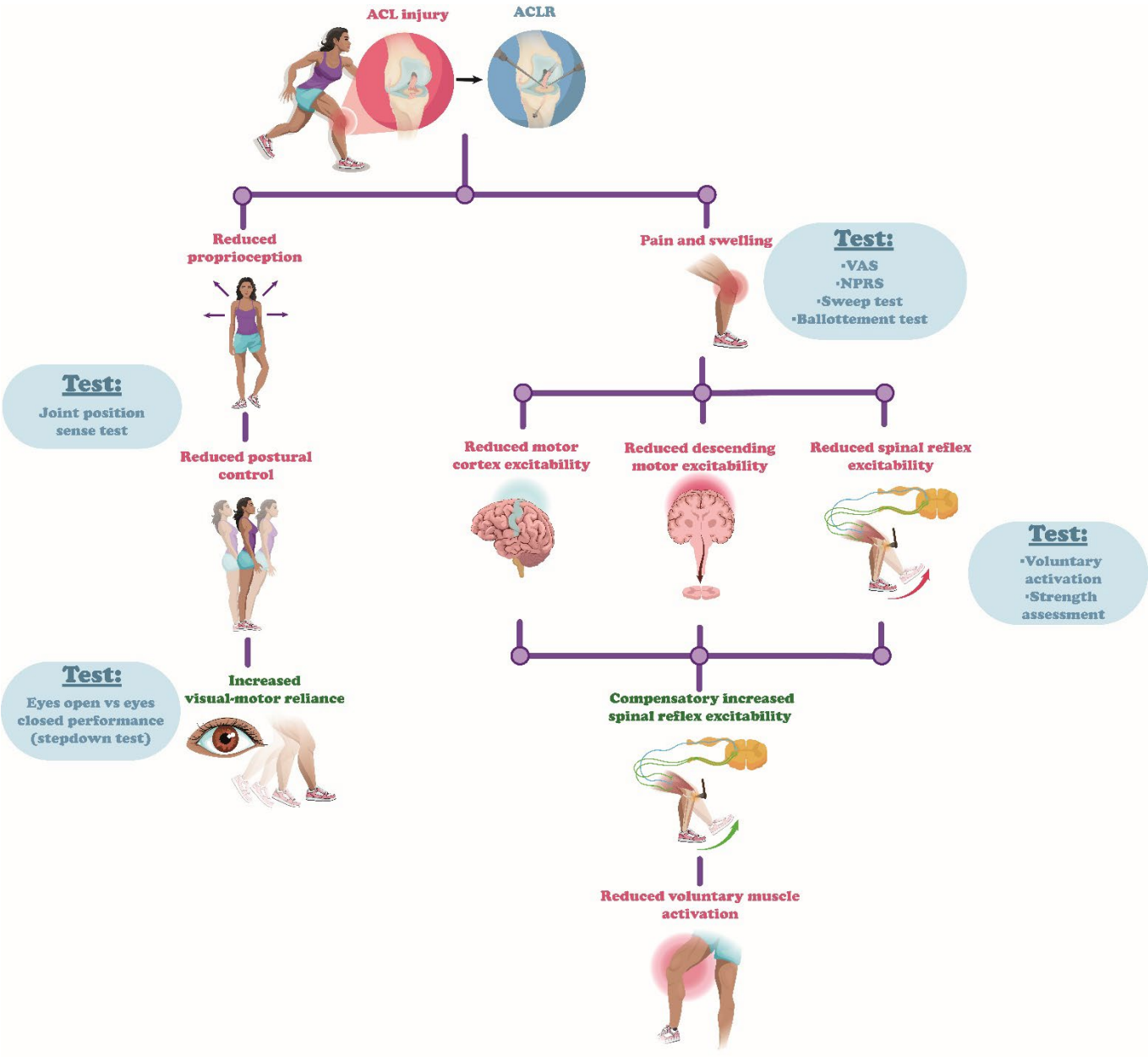


Figure B6. Stages of sensorimotor dysfunction that occurs following anterior cruciate ligament (ACL) injury and ACL reconstruction (ACLR).

Sensorimotor dysfunction may persist following ACL injury and occurs across all aspects of the sensorimotor system: afferent pathways, efferent pathways and central processing. With the difficulty of assessing central processing in clinical practice, clinicians should therefore focus on assessing the somatosensory, visual and efferent systems. Routine assessment of the somatosensory system (JPS testing, pain and effusion testing) and visual system (visual-motor reliance testing and visual-motor processing testing) will help to guide clinician decision making along the rehabilitation journey of their athletes. Similarly, assessing efferent function through strength testing and EMG assessment for voluntary activation can be easily implemented into clinical practice.

B7 Key Points

Findings: Sensorimotor dysfunction can occur following an ACL injury. It occurs across the somatosensory, visual and efferent systems.

Implications: Assessments should occur along the three systems. JPS, pain and effusion tests can be completed for the somatosensory system. Visual-motor reliance testing and visual-motor processing testing can be conducted for the visual system. Finally, strength testing and voluntary activation testing can be completed for the efferent system.

Caution: More research is required for visual-motor reliance and visual-motor processing tests to identify normative values for the various tests and to determine if there is a link to future risk of reinjury

Supplementary I

Joint position assessment

Relph and colleagues (2016) were able to demonstrate via an image recorded angulation test that elite athletes, even a year post-ACLR, had reduced JPS function as compared to sport and age-matched athletes (Relph and Herrington, 2016b). To complete the testing method as per the study (Relph and Herrington, 2016b; Relph and Herrington, 2015b), have the athlete sitting with their knee over the edge of a plinth. The athlete is blinded throughout the test. Then, place three markers placed on their leg: (1) lateral femoral condyle, (2) lateral malleolus, and (3) a point along a line between the greater trochanter and lateral femoral condyle (see Figure S1). Setup a camera on a tripod 3 metres away in-line with the lateral femoral condyle. Passively extend the athlete's knee (with hand placement under the distal shin) to the target angle (which was randomly selected within a range of 30-60°). Hold the knee at the target angle for 5 seconds. Passively bring the athlete's knee back to the starting position (leg comfortably relaxed in naturally flexed position whilst sitting). Then, instruct the athlete to actively extend their knee to the angle that they believe it was held at by the clinician. A photograph is taken on 6 occasions: first at the target angle when the leg was passively held there, and then for each of the 5 repetitions when the participant stops actively moving their knee and reports that they are at the target angle. The angles are then measured from the photographs using digitising software, such as 'autoCAD' (*Autodesk, USA*) or free software such as Kinovea (https://www.kinovea.org) and ImageJ (https://imagej.net/ij), and the difference between the target angle and the athlete's attempted replication of the angle is calculated. The average of difference between each of the 5 reps is taken as the measurement of JPS ability. The testing procedure has good inter-rater reliability (ICC=0.98) and intra-rater reliability (ICC=0.96) (Relph and Herrington, 2015b), with a smallest detectable change of 1.10° for knee

flexion (standard error of measurement 0.40°) and 1.35° for knee extension (standard error of measurement 0.60°) (Relph and Herrington, 2015b). A difference of greater than 5.3° between the ACLR limb and the uninjured limb of the athlete represents poor proprioceptive ability in the ACLR limb (Relph and Herrington, 2016b).

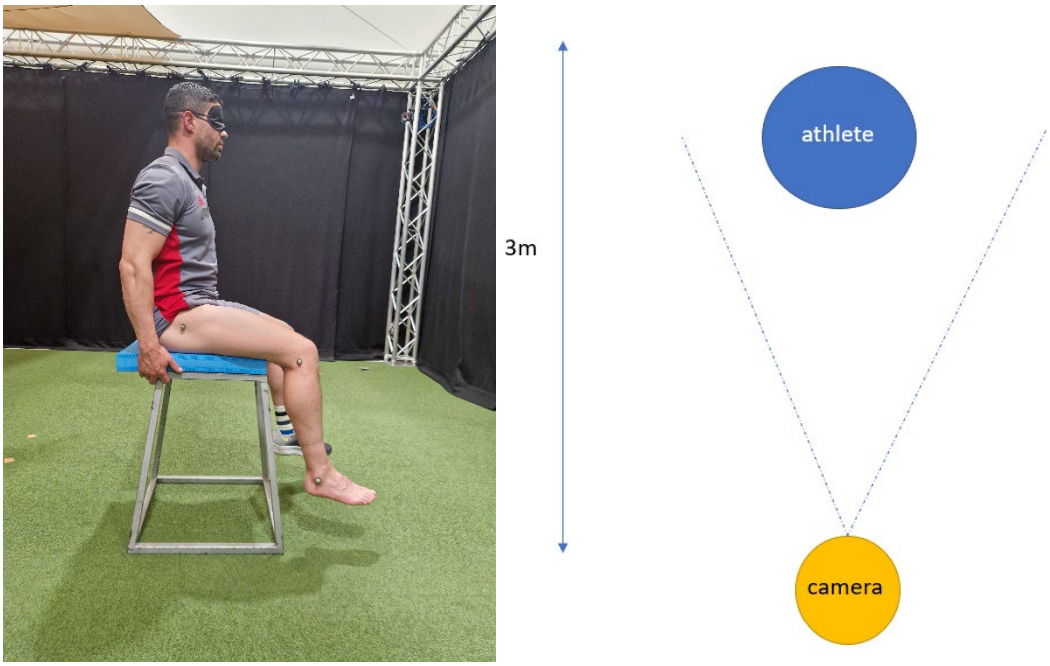


Figure S1. Joint position assessment set up

Supplementary II

Effusion assessment

Supplementary video on Effusion tests

Effusion Tests.mp4

Supplementary III

Stepdown test for assessing visual-motor reliance

The following protocol is currently unpublished. A force plate is required for this assessment. A 20-centimetre step is placed behind the force plate. The athlete is barefoot for the test. The athlete starts on the step with their hands on their hips. They are instructed to step onto the force plate with a single leg and achieve stability as quickly as possible whilst also maintaining their landing posture for 20 seconds. The landing posture of the leg is not standardised. Three trials are conducted for both legs. The athlete then repeats the procedure whilst wearing a blindfold to obstruct vision. Trials were deemed invalid if the non-testing leg touches the ground, a double contact occurred with the testing foot, the blindfold was removed or their hands were removed from their waist.

The medial-lateral and anterior-posterior data are then processed using a sequential estimation technique (Colby et al., 1999; Byrne et al., 2021) to calculate time to stability (TTS) in each direction

(medial-lateral and anterior-posterior). A visual-motor reliance index is then calculated using the TTS eyes open versus the eyes closed:

$$VR\ index = \left(\frac{[TTS\ (blinded) - TTS\ (full\ vision)]}{TTS\ (full\ vision)}\right)\ x\ 100$$

Supplementary IV

Isokinetic dynamometer assessment of quadriceps and hamstrings strength

A systematic review (Undheim et al., 2015) recommended a standardised protocol when assessing quadriceps and hamstrings strength with an isokinetic dynamometer. It is the current protocol used at the Sports Surgery Clinic (Dublin, Ireland) as part of its ACL research program (O'Connor et al., 2020; O'Malley et al., 2018). The participant is seated comfortably with the torso and limb to be tested fixed to the chair and testing arm, respectively. Three sets of five repetitions (first set being a sub-maximal familiarisation set) of concentric knee flexion and extension are completed. A minute rest is provided between each of the sets and the knee is tested between a range of 0-100°, at a speed of 60°/second, and gravity correction employed. Peak torque of the quadriceps and hamstrings represent their strength. Values that athletes should aim to return to are quadriceps peak torque of 240% to 270% body mass, and hamstrings peak torque of 150% to 160% body mass (O'Malley et al., 2018).

Supplementary V

Use of surface EMG biofeedback devices for assessment of voluntary quadriceps activation

Two electrodes are placed over the vastus medialis and two over vastus lateralis (see Figure S5). Athletes sit upright in a chair with their back supported, extend their knee to neutral and contract their quadriceps maximally. Several repetitions are performed until a consistent EMG recording is found. The athlete then lies on their back with their leg extended. They contract their quadriceps maximally and perform a straight leg raise. Several repetitions of the straight leg raise are performed until a consistent EMG recording is taken. A reduction in voluntary quadriceps activation is determined by a reduction in the EMG recording in the ACLR limb as compared to the uninjured limb either during the straight leg raise or the knee extension task. Due to the potential for noise created by electrode placement being slightly different, we suggest that a difference of greater than or equal to 20-30% is what is used in the clinic to determine if there is a reduction in voluntary activation (Pamukoff et al., 2017; Cui et al., 2023).



Figure S5. Electrode placement for surface EMG assessment of the quadriceps.

Appendix C

Sensorimotor dysfunction following anterior cruciate ligament injury (Part 2): How can we rehabilitate it?

The purpose of this study was to follow on from the previous clinical commentary and provide clinicians a summary of rehabilitation methods to rehabilitate the various facets of sensorimotor dysfunction that occurs following ACL injury.

C1 Abstract

Background

Sensorimotor dysfunction following anterior cruciate ligament (ACL) injury and subsequent ACL reconstruction (ACLR) may lead to errors in motor planning and execution. This dysfunction occurs even after athletes have completed current standard ACLR rehabilitation. Therefore, clinicians need to implement strategies to rehabilitate sensorimotor dysfunction better.

Clinical question

How can clinicians improve their rehabilitation of sensorimotor dysfunction following ACLR? The aim of this clinical commentary is to review methods that may help to optimise rehabilitation by targeting the sensorimotor dysfunction following ACL injury.

Key results

Rehabilitation should focus on two priorities: (1) improving peripheral and central efferent function, and (2) improving somatosensory function and reducing reliance on the visual-motor system.

Clinical application

Somatosensory function can improve with proprioceptive training but should be implemented within the first six weeks of injury/surgery to minimise the chance of increased reliance on the visual-motor system. Methods to increase the complexity of proprioceptive training includes varying the: (1) type of task (e.g. jumping, decelerating, etc), (2) the visual information utilised during the task, (3) the cognitive loading during the task, and (4) perturbations. The use of visual distraction training may be useful in challenging an athlete during sports-specific training and reduce the reliance on the visual-motor system. Improving peripheral and central efferent function involves utilising regular cryotherapy and TENS in the early stages to minimise the pain and improve muscle recruitment. Also, throughout rehabilitation, strength training, NMES and surface EMG biofeedback methods improve central and peripheral efferent function when prescribed at a high intensity.

Key words

Anterior cruciate ligament, sensorimotor dysfunction, treatment, rehabilitation, afferent, efferent

C2 Introduction

Rehabilitation following ACL injury and ACLR is a lengthy process for athletes, requiring at least 9-12 months of contact with their treating clinician. Even after completing rehabilitation there remains a high risk for reinjury, especially in the adolescent athlete, due to multiple factors (Webster et al., 2014; Salmon et al., 2005). One such factor may be lingering sensorimotor

dysfunction leading to errors in motor planning and execution (Swanik, 2015; Grooms et al., 2015c), as described in Part 1 (Vitharana et al., 2025a). Rehabilitation following ACLR traditionally focuses on progressing through several stages: (1) achieving a 'calm' knee joint (full ROM and no effusion) early post-surgery, (2) regaining strength and power, (3) the introduction of linear and multi-directional running, and (4) reintroduction to sport (van Melick et al., 2016). Clinicians use various methods to help athletes achieve these goals but with lingering sensorimotor dysfunction, it is possible that clinicians may not be using effective strategies to target these specific deficits. Therefore, the aim of this clinical commentary is to review methods that may help to optimise rehabilitation by targeting the sensorimotor dysfunction following ACL injury and ACLR. Similar to Part 1, this clinical commentary will have evidence-based suggestions that is driven by our clinical practice in a sports medicine facility and mechanistic research. A definition of terms that may be encountered in the text are listed in Table C2.

Table C2. Definition of terms related to sensorimotor dysfunction that may be encountered in the text

Term	Definition
Sensorimotor	Is a system integral to motor control within the body that encompasses afferent, efferent and central processing pathways
Efferent	Includes pathways that takes neural activity to the muscles to create movement
Central efferent function	Focuses on efferent activity within the brain
Peripheral efferent function	Focuses on efferent activity in the descending motor column and spinal reflexive activity
Afferent	Includes pathways that takes neural activity from the sensory systems to the brain
Somatosensory	Sensory system focused on perception of position, movement, touch pressure and pain
Proprioception	Is a function of the somatosensory system that relates to the body's ability to sense position of its body segments in space

C3 Clinical question

How can clinicians improve their rehabilitation of sensorimotor dysfunction following ACL injury? Dysfunction within the afferent and efferent pathways following ACL injury and ACLR can be summarised by Figure 1 which was adapted from Part 1 of the clinical commentary (Vitharana et al., 2025a). The two events that are pertinent to clinicians are: (1) reduced efferent function, and (2) increased reliance on the visual-motor system (Figure C3). As described in Part 1 of the clinical commentary (Vitharana et al., 2025a), the reduced efferent function results from both reduced central and peripheral efferent factors. In addition, the increased reliance on the visual-motor system occurs in response to altered somatosensory function, namely altered proprioceptive information following the damage to proprioceptors within the ACL. Therefore, clinicians managing athletes following ACL injury and ACLR should focus their rehabilitation on the following areas to effectively manage sensorimotor dysfunction. (figure 1):

1. Improving peripheral and central efferent function
2. Improving somatosensory function and reducing reliance on the visual-motor system

The following sections review the methods of rehabilitation targeting the above priorities and providing guidelines for how clinicians may implement these in practice.

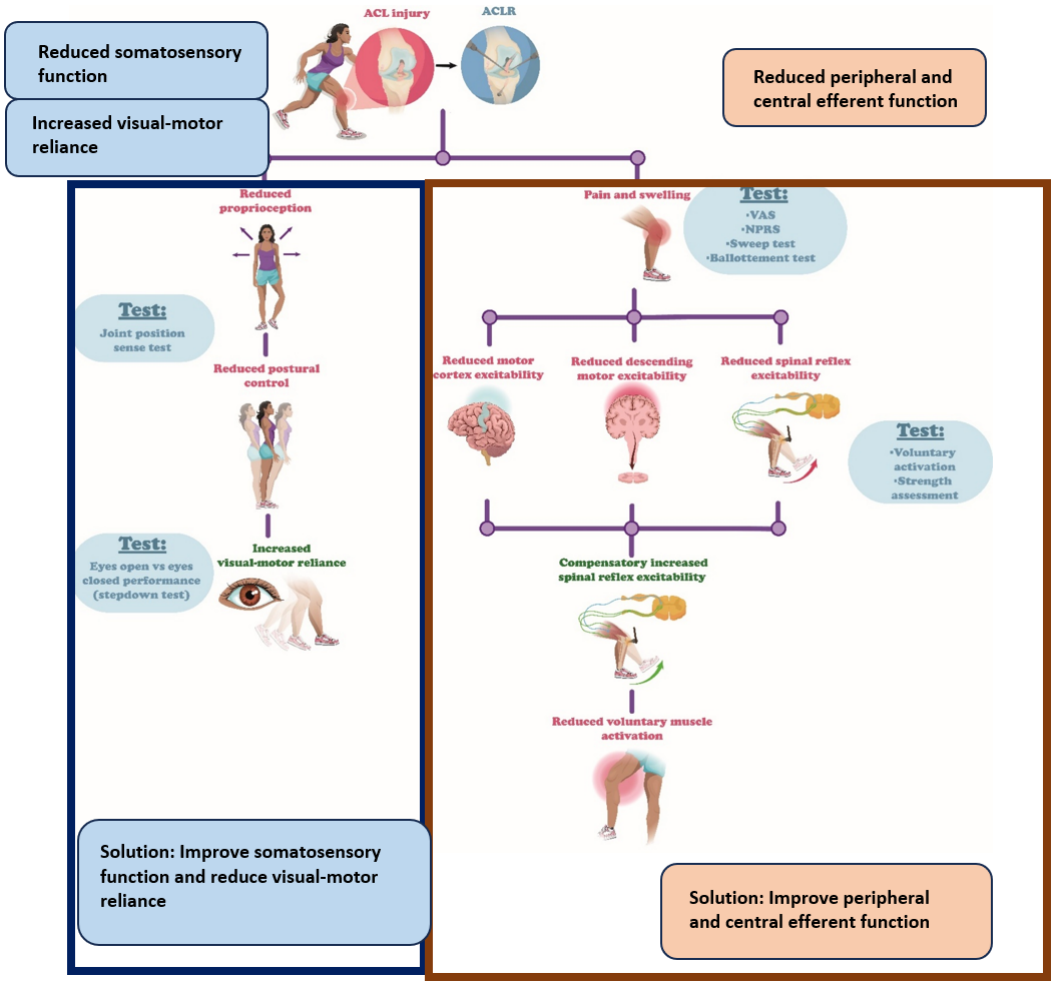


Figure C3. Sensorimotor dysfunction following ACL injury and ACLR. Also outlines the two priorities for clinicians rehabilitating athletes with sensorimotor dysfunction.

C4 Improving peripheral and central efferent function

Improving peripheral and central efferent function is important to ensure complete restoration of strength and to avoid developing any compensatory changes to an athlete's movement technique. Peripheral efferent dysfunction is predominantly found in the first few weeks post-injury which results in a reduction in spinal reflex excitability, whilst central efferent dysfunction manifests as descending motor inhibition sub-acutely following surgery (Lepley et al., 2015; Pietrosimone et al., 2015b).

Early-stage rehabilitation

Pain and swelling within the knee joint lead to reductions in the spinal-reflexive pathway and quadriceps activation (Konishi et al., 2002; Pietrosimone et al., 2022). It should be standard practice that regular movement of the knee, lower limb strength exercises and gait retraining be completed early in rehabilitation to help to reduce pain and swelling in the knee (Kotsifaki et al., 2023). However, further strategies to improve pain and swelling should be used aggressively in the early stages of rehabilitation to augment recovery. Methods include pain medication, transcutaneous electrical nerve stimulation (TENS) and cryotherapy (Sonnery-Cottet et al., 2019).

Pain medication strategies can vary amongst surgeons. Post-operative pain is generally at its worst in the first three days and hence nerve blocks are commonly used to reduce the pain and allow early ambulation and discharge (Bolia et al., 2021). Nerve blocks result in significantly reduced post-operative pain and analgesic use (Davey et al., 2021). Non-steroidal anti-inflammatory medications are commonly used in outpatient care following an ACLR (Bourne, 2004). They have been shown to significantly reduce pain and the need for analgesic medication following ACLR (Secrist et al., 2016). With any medication, they should be appropriately prescribed by the treating physician and surgeon within the scope of their respective regulatory bodies.

TENS devices apply an electrical impulse to the large diameter afferent nerve fibres via electrodes placed around the injured structure (Radhakrishnan and Sluka, 2005). The afferent information is processed in the central cortex which activates descending inhibitory pathways, resulting in a reduction in peripheral and central hyperalgesia (DeSantana et al., 2009). A review by Bjordal and colleagues (2007) (Bjordal et al., 2007) found that TENS is able to reduce knee pain by 36% if the TENS dosage is set to: a strong non-noxious stimulus, low frequency setting of 1-8Hz, high frequency of 25-120Hz, 20 minutes treatment time and at least 5 treatment sessions (Bjordal et al., 2007).

Cryotherapy is commonly used in the management of pain following soft tissue injuries. It significantly reduces pain and the reduced need for analgesic medication (Raynor et al., 2005;

Martimbianco et al., 2014). Cryotherapy devices, especially those which include pneumatic pressure to provide compression to the knee, such as 'Game Ready' (*CoolSystems Inc, USA*) and 'Cryocuff IC Cooler' (*DonJoy Global, USA*), reduce pain significantly more than ice packs alone following ACLR (Murgier and Cassard, 2014; Waterman et al., 2012). Waterman and colleagues (2012) (Waterman et al., 2012) compared the use of a cryotherapy with compression device against a standardised ice pack following ACLR. They demonstrated that cryotherapy-compression significantly reduced participants' pain (by 50%) and led to the cessation of pain medication (83% of participants ceased medication by 6 weeks) as compared to no significant change in pain in those using standard ice packs and only a small portion of these participants ceasing pain medication (23% of participants ceased medication by 6 weeks).

In summary, to improve efferent function in the early stages of rehabilitation, clinicians should encourage athletes to utilise cryotherapy with compression devices regularly (ideally three times a day or once a day if there are accessibility barriers) for the first 6 weeks and apply TENS daily for 20 minutes for the first 4-6 weeks.

Throughout rehabilitation

Strength training is the mainstay of ACLR rehabilitation and provides a powerful stimulus to improve both peripheral and central efferent function. In the uninjured population, strength training increases motor unit excitation and recruitment, increases corticospinal excitability and reduces intracortical inhibition (Mason et al., 2020; Kidgell et al., 2017; Duchateau et al., 2006). Changes in neural excitability occur within strength training sessions and can be maintained between sessions (Mason et al., 2020). With strength training positively affecting efferent function, it raises questions as to why efferent dysfunction is measured so commonly in ACLR individuals who have participated in strength training (Lisee et al., 2019; Lepley et al., 2015; Pietrosimone et al., 2015b). A study by Colomer-Poveda and colleagues (2020) demonstrated that training intensity is

a key factor in improving corticospinal excitability. Significant increases in corticospinal excitability were found when participants trained at 75% of maximum voluntary contraction, whilst no changes occurred to those who exercised at 25% of maximum voluntary contraction. Although Welling and colleagues (2019) did not measure neural excitability, they were able to demonstrate that a progressive resistance program (resistance built up overtime to >90% of 1 repetition maximum) was able to increase the quadriceps and hamstrings strength of ACLR athletes to the same level as healthy controls by 7 months post-surgery. The results of these two studies suggests that training intensity is important during ACLR rehabilitation and participants in previous research highlighting efferent dysfunction research may potentially not have trained at a high enough intensity to achieve symmetrical strength and to improve their efferent function back to baseline.

Neuromuscular electrical stimulation (NMES) and surface electromyography (EMG) biofeedback can be used as adjuncts to strength training to improve efferent function (Glaviano and Saliba, 2016; Conley et al., 2021). **NMES** commonly uses a handheld device to apply an electrical current to muscles via electrodes placed on the skin (e.g. 'Compex', *DonJoy Global, USA* and 'Neurotrac Sport', *Verity Medical Ltd, UK*). The electrical current elicits a contraction in the muscle. Because athletes in early rehabilitation have diminished spinal reflexive activity and reduced voluntary quadriceps activation (Lepley et al., 2015), NMES provides an avenue to contract the quadriceps without the risk of heavy loads going through the joint if the athlete was to otherwise perform a high intensity strength exercise. NMES also preferentially recruits type II muscle fibres which may minimise the risk of selective atrophy of the these muscle fibres (Maffiuletti, 2010; Toth et al., 2020) and hence improve force production from the quadriceps (Hauger et al., 2018). Reviews have demonstrated that NMES in addition to exercises and physiotherapy results in significantly better quadriceps strength when compared to exercises and physiotherapy alone (Wright et al., 2008; Hauger et al., 2018; Culvenor et al., 2022). NMES was mainly effective when used at high intensities with the contraction time set to 15-20 seconds and rest time set to 15-50 seconds (Delitto et al., 1988; Snyder-Mackler et al., 1991). NMES was generally used 5-7 days per week for the first 4-12

weeks post-ACLR but the frequency of this may need to be reduced if accessibility barriers exist for athletes (Snyder-Mackler et al., 1991; Delitto et al., 1988; Feil et al., 2011).

Surface EMG biofeedback devices are also commonly handheld devices, with electrodes placed over the motor units of the target muscles (e.g. 'Neurotrac Simplex', *Verity Medical Ltd, UK* and 'mTrigger', LLC, *Delaware, USA*). They measure the magnitude of motor unit recruitment and provide that information to the user on an easy-to-read display. EMG biofeedback training is an active modality in which the clinician can set a target for muscle activity for the athlete to achieve, and the athlete receives an auditory or visual stimulus each time that they achieve this goal. This differs from NMES which is a passive modality. By this mechanism, EMG biofeedback training provides an external focus of attention to their training and can improve corticospinal excitability, which is otherwise unaffected by NMES (Pietrosimone et al., 2015a). EMG biofeedback training has been repeatedly demonstrated to increase quadriceps strength significantly greater than those who do not utilise feedback during their training following knee surgery (Croce, 1986; Levitt et al., 1995). EMG biofeedback can be completed with both isometric and isotonic exercises (Yilmaz et al., 2009; Anwer et al., 2011). The current literature suggests that a dosage of 5-7 days per week (Anwer et al., 2011; Kokic et al., 2023) is effective in improving strength, however accessibility barriers for athletes may mean this frequency is not possible. Therefore, athletes may find it easier to focus on using EMG biofeedback training during their strength sessions.

In summary, improving efferent function via improving spinal reflexive activity, corticospinal excitability and intracortical excitability is essential throughout rehabilitation. Progressive strength training at a high enough intensity (>75% of 1 repetition max) to elicit strength and hypertrophy changes, is a powerful stimulus to all components of the efferent system. To optimise an athlete's rehabilitation, NMES could be used during the first 6 weeks post-surgery to minimise type II muscle fibre atrophy in the quadriceps (Maffiuletti, 2010; Toth et al., 2020) and to maintain or increase spinal reflexive activity to the quadriceps that would otherwise be inhibited due to the pain and

swelling. As the swelling reduces and the athlete can voluntarily activate their quadriceps, NMES use would be reduced such that it is used on non-strength training days (once or twice a day depending on accessibility barriers of the athlete) and as part of the warm up on a strength session (5-10 minutes in preparation part of session). The athlete would then also add EMG biofeedback training to their program during strength sessions until no clinically relevant strength or efferent deficit existed between limbs. Figure C4 summarises the key take home messages for clinicians with regards to each modality: TENS, cryotherapy, NMES and strength training

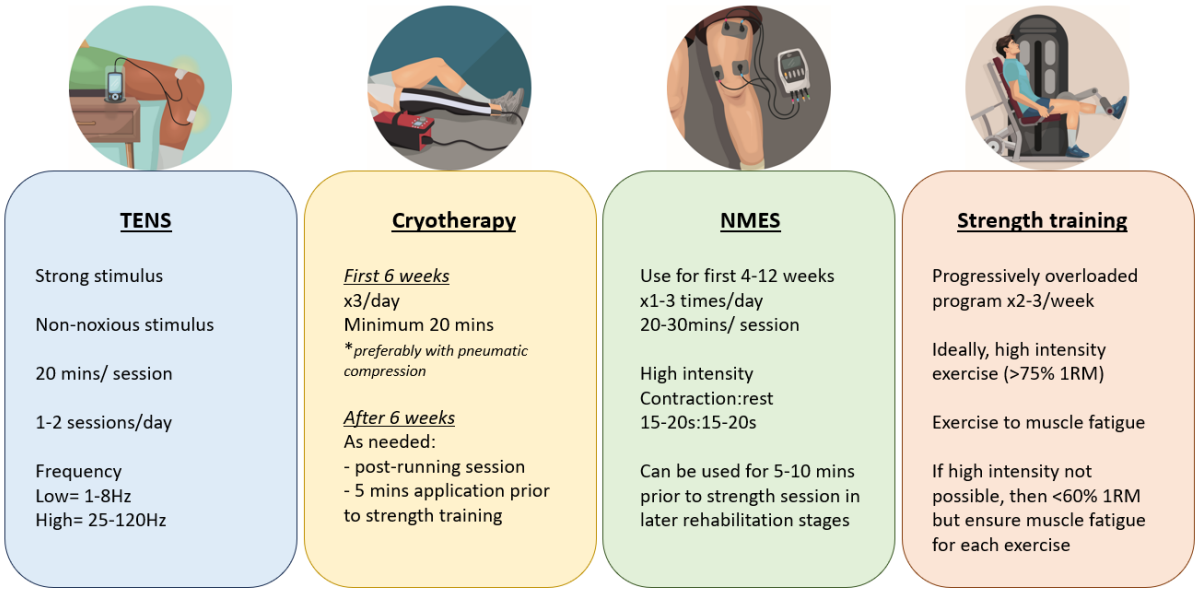


Figure C4. Take home messages for clinicians regarding treatment modalities.

Abbreviations: *TENS= transcutaneous electrical stimulation, NMES= neuromuscular electrical stimulation, mins= minutes, Hz= Hertz, s= seconds, RM= repetition maximum*

C5 Improving somatosensory function and reducing reliance on the visual-motor system

Improving somatosensory function early in rehabilitation is essential to restore normal function, reduce re-injury risk, and minimise reliance on the visual-motor system (Grooms et al.,

2015a). Somatosensory dysfunction primarily results from the loss of afferent feedback from the ACL and secondarily from pain and swelling. Therefore, early rehabilitation strategies should focus on improving an athlete's proprioceptive ability and reducing pain and swelling. Regrowth of the proprioceptor nerve fibres into the ACL graft can take months, with no exact time period identified (Denti et al., 1994; Barrack et al., 1997). Therefore, improving an athlete's proprioceptive ability in early-stage rehabilitation primarily focuses on improving the control of the surrounding muscles and joints to compensate lack of proprioceptive information from the ACL graft. In the case of non-operatively managed ACL injuries, this focus on control of the surrounding muscles and joints needs to be completed throughout rehabilitation as the remaining proprioceptors in the ACL stump may provide altered information (Denti et al., 1994; Dhillon et al., 2010). Strategies to reduce pain and swelling will not be discussed here as they were covered in the section above, 'improving peripheral and central efferent function', and include pain medication, TENS and cryotherapy.

Proprioceptive training aims to improve proprioceptive function with a focus on using somatosensory afferent information in the absence of vision (Aman et al., 2015). A review found that proprioceptive training significantly improved proprioceptive ability across a range of injuries, including knee pathology (Aman et al., 2015). Whilst proprioceptive training reduces the incidence of ACL primary injury in field-based athletes (Dargo et al., 2017; Ladenhauf et al., 2013; Mandelbaum et al., 2005), there is a lack of research following ACLR to determine its effectiveness.

Implementation of proprioceptive training very early in rehabilitation is thought to be important as reliance on the visual motor system occurs within the first six weeks after surgery (Lehmann et al., 2021a). Proprioceptive training within the clinic predominantly takes the form of balance exercises. It is important that proprioceptive training is programmed into an athlete's program such that the complexity of the drill progressively increases. Complexity can be progressed through: (1) the type of task (e.g. stationary standing or a landing task), (2) the amount of visual information (e.g. full vision, blinded vision or partial blinding), (3) the amount of cognitive loading (e.g. dual task loading

and cognitive task) and (4) the amount of perturbation (e.g. foam surface or external perturbation application). Figure C5 details a few options for each factor.

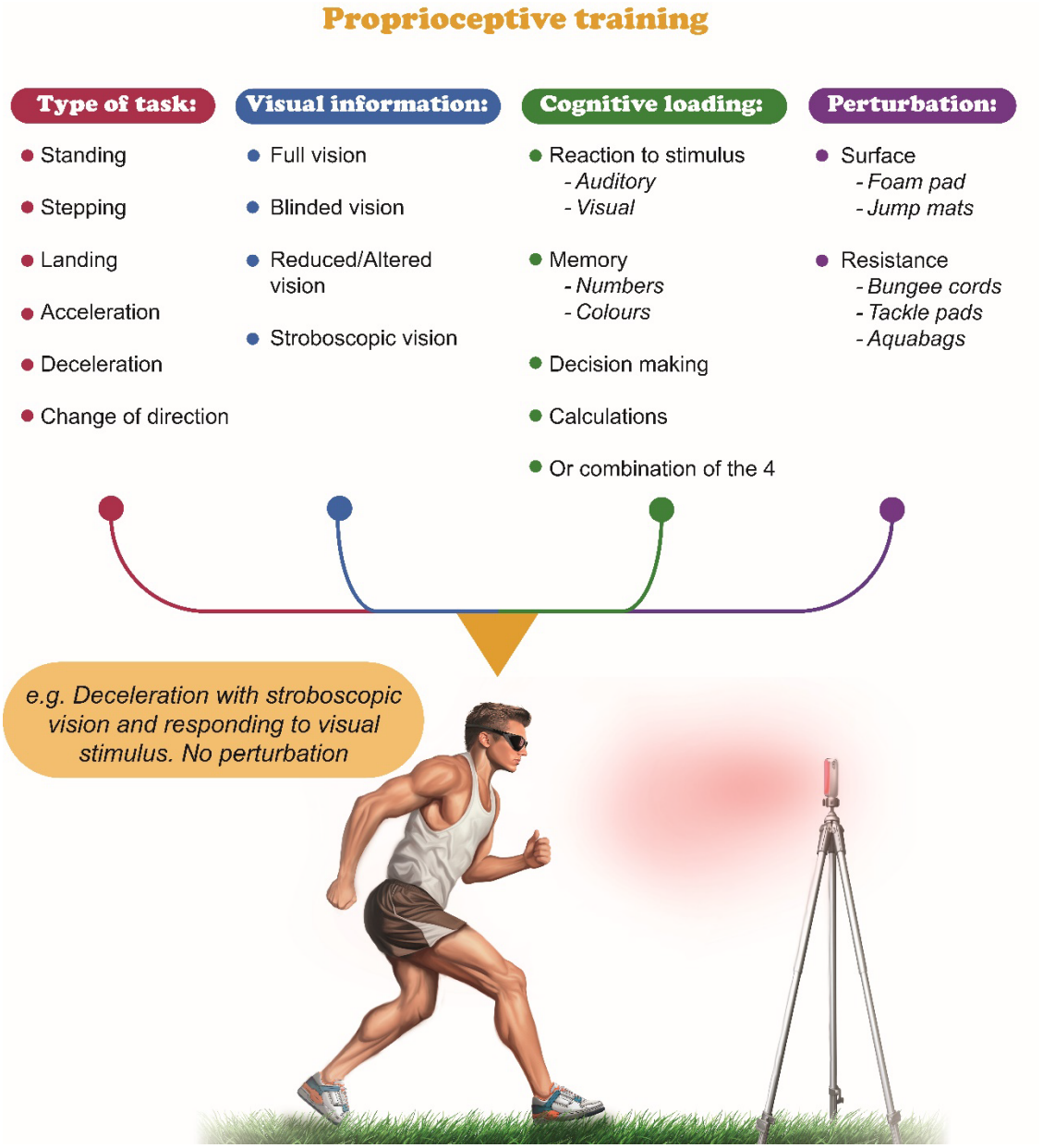


Figure C5. Framework outlining factors that need to be considered when creating proprioceptive drills: type of task, visual information, cognitive loading and perturbation.

Factor 1- Type of task

Many of the tasks used for proprioceptive training are commonly low-load and low-velocity in nature, such as single-leg standing or squatting. Whilst this is appropriate initially after surgery, as

rehabilitation progresses, exercises need to progress into higher loads and velocities in multiple movement planes, such as stepping tasks, landing tasks, deceleration tasks and change of direction tasks.

Factor 2- Visual information

Maintaining postural control or executing a movement requires the athlete to process somatosensory and visual information so that appropriate muscle actions can be executed (Ivanenko and Gurfinkel, 2018a). If visual information is removed, then the athlete will rely more on their proprioception. Hence, clinicians will commonly remove vision during a proprioception drill (e.g. standing on one leg eye closed). However, as the task progresses to a more dynamic task, such as a landing task, then being blinded may make the task too difficult to complete or dangerous. A method that can be used to reduce visual information is the use of stroboscopic glasses (e.g. 'Senaptec', *Oregon USA*). Training with stroboscopic glasses facilitates motor skill acquisition.(Bennett et al., 2018) These glasses flicker between being transparent and opaque so that visual information is partially reduced. The frequency with which the glasses flicker can be altered by clinicians so a single task can have several levels of difficulty. An example of this could be an athlete being tasked to jump and land on a single leg. Initially the task can be completed with a high frequency on the stroboscopic glasses (more visual information is obtained) and as the athlete progresses, the frequency is reduced so that there are longer periods of opacity (less visual information is obtained). No research to date has been conducted to determine the optimal dosage for stroboscopic training in the ACLR population. Training dosage in studies investigating skill acquisition vary from short (ten minutes) daily sessions to longer (30-50 minutes) sessions two to three times per week (Das et al., 2023a; Appelbaum et al., 2012; Mitroff et al., 2013). The authors have found three sessions per week with the stroboscopic glasses to be the most practical in exposing athletes to this training. If clinicians do not have access to stroboscopic glasses, then

glasses with pinholes or shutters can be utilised but may not be as effective as the stroboscopic glasses.

Factor 3- Cognitive loading

ACL injuries commonly occur in chaotic sporting environments. Athletes need to coordinate movements whilst processing multiple stimuli (e.g. position of opponents and position on the field) and making multiple decisions (e.g. state of the game, whether to pass and remembering coaches gameplay instructions). These factors add to the cognitive burden in athletes and may lead to errors in movement coordination and execution (Swanik, 2015). Therefore, within rehabilitation, it is important that clinicians progressively add cognitive load to proprioceptive tasks to challenge their athletes. Cognitive load can be made in the form of: (1) reaction to a stimulus, (2) memory task, (3) decision making task, (4) calculations or (5) a combination of the 4 forms.

Factor 4- Perturbation

Perturbations are unexpected forces applied to the athletes to induce a reactive control of their posture (McCrum et al., 2022). It has been suggested that drills incorporating perturbation should meet two conditions: (1) the external perturbation should induce a rapid and sudden motor response and (2) the perturbation should cause a loss of stability (e.g. a stumble or fall) without a sufficient motor response (McCrum et al., 2022). Perturbation training is effective in improving balance in individuals following ACL injury (Méndez-Bouza et al., 2023), chronic ankle instability (Mollà-Casanova et al., 2021; O'Driscoll and Delahunt, 2011) and preventing falls (Mansfield et al., 2015).

C6 Conclusion

There are a range of interventions (see table S5.1 in the supplementary file) that can be utilised to target sensorimotor dysfunction following ACL injury. The two goals of rehabilitation are: (1) to improve peripheral and central efferent function, and (2) to improve somatosensory function and reduce the reliance on the visual-motor system. There is strong evidence for the use of interventions such as strength training, NMES and surface EMG biofeedback to improve efferent function. Whilst these methods are effective in improving efferent function, clinicians need to be aware of prescribing the interventions at the appropriate intensity to achieve best results. Similarly, there is good evidence for the use of certain interventions (proprioceptive training, TENS and cryotherapy) to improve somatosensory function. However, currently there is a lack of evidence examining whether these interventions result in a reduced reliance on the visual-motor system. Increasing the complexity of proprioceptive training across a number of factors (type of task, amount of visual information, cognitive loading and perturbations) may help to improve the effectiveness of proprioceptive training in reducing visual-motor reliance.

C7 Key Points

Findings: To improve sensorimotor function following ACL injury, clinicians should aim to (1) improve peripheral and central efferent function and (2) improve somatosensory function and reduce reliance on the visual-motor system. Interventions can be implemented early in rehabilitation and progressed over time.

Implications: Clinicians can utilise strength training, NMES and surface EMG biofeedback to improve local and central efferent function. Whilst, improving somatosensory function can be achieved through proprioceptive training, TENS and cryotherapy.

Caution: There is a lack of prospective research to identify if proprioceptive training can reduce visual-motor reliance.

Supplemental VI

Table S5.1. List of available interventions to target sensorimotor dysfunction following ACLR.

Interventions	Purpose	Equipment needed	Facilitators	Barriers
Pain medication	Allows clinicians to moderate an athlete's pain so that they can progress with rehabilitation	Nil	Wide range of medications that can be effective in reducing pain.	Cost of medication and potential side effects of medications. Could create dependence on medication.
TENS	Electrical pads placed around the knee to deliver a non-noxious electrical impulse to reduce pain from the knee.	TENS machine and pads	Effective in reducing knee pain	Cost of purchasing a device. Time cost with athletes required to use the device regularly
Cryotherapy	Ice packs applied around the knee to cool the skin temperature down. Ideally, this will be used in combination with a pneumatic compression device to be most effective in reducing knee pain.	Ice packs. Ideally a pneumatic compression device as well.	Effective in reducing pain and easy to complete if just using ice packs.	Cost of renting or purchasing the pneumatic compression and cryotherapy device. Time cost with the athletes required to ice regularly in the early stages post-operatively
NMES	Electrical pads placed over the target muscle (usually quadriceps) to deliver an electrical impulse that results in a muscle contraction.	NMES machine and pads	Effective at improving strength and minimising atrophy.	Cost of purchasing a device. Time cost with athletes required to use the device regularly
Surface EMG biofeedback	Electrical pads placed over the target muscle. Athlete is asked to complete an exercise or voluntarily contract the muscle.	Surface EMG device and pads	Effective in improving central efferent drive and can be paired easily with strength exercises.	Cost of purchasing a device. Time cost with athletes required to use the device regularly

	The device will provide an output as to whether the target muscle activity is achieving the threshold set up the clinician.			
Strength training	A progressively overloaded strength program three times a week and ensuring the athlete works to muscular fatigue will allow clinicians to positively affect an athlete's strength and hypertrophy.	Access to a gym or weights for within the house	Effective in improving strength and hypertrophy following ACLR.	Financial cost of either purchasing weights or gym membership. Accessibility to gyms can be an issue depending on geographical location. Needs appropriate prescription of exercises by taking into account ACLR graft donor site, training age and technique competency.
Proprioceptive training	Using a framework, movement tasks can be manipulated by changing cognitive, visual or perturbation demands to challenge an athlete's proprioceptive ability.	May need items such as blindfolds, strobe glasses, bungee cords, foam pads, etc.	Exercises can be done in any location so athletes can easily complete the exercises.	Cost of purchasing equipment. The most effective training dose post-ACLR is not quite known.

Abbreviations: *TENS*= transcutaneous electrical nerve stimulation, *NMES*= neuromuscular electrical stimulation, *EMG*= electromyography, *ACLR*= anterior cruciate ligament reconstruction

Appendix D

Results table of somatosensory studies examined within scoping review Chapter 2

Table D1. Summary table of tables examining between limb differences in ACLR cohort (ACLR limb versus uninjured limb)

Level of somatosensory system	Authors	Participant information	Time from surgery (months)	Outcome measure used	Task	Results	Testing tool
Central processing							
Significant reduction in function ($p<0.05$)	Valeriani et al (Valeriani et al., 1999) Cohort study	ACLR (n=7) Unclear age profile	Atleast 24	Somatosensory evoked potentials via EEG	Stimulation of the common peroneal nerve	ACLR limb significantly reduced performance as compared to uninjured limb.	EEG

	Bartels et al (Bartels et al., 2019) Longitudinal study	ACLR (n=30) 30 ± 12.2 yrs	24	Posturography during standing under different environmental constraints	Double leg standing with manipulations of head position, surface under the feet and varying visual conditions	Significant improvement in somatosensory system's involvement during balance task from preoperative to 24 months postoperative (medium effect size η^2= 0.07)	Posturography utilising 'Interactive Balance System'
	Bartels et al (Bartels et al., 2018)	ACLR (n=54) 30.5 ± 10.9 yrs	3	Posturography during standing under different environmental constraints	Double leg standing with manipulations of head position, surface under the feet and varying visual conditions	Significant improvement in the somatosensory system's involvement during balance (large effect size η^2= 0.12)	Posturography utilising 'Interactive Balance System'
	An et al (An et al., 2019) Comparative study	ACLR (n=17) 26.9 ± 5.6 yrs Healthy control (n=17) 22.3 ± 3.8 yrs	41.8 ± 24.7	EEG recording of somatosensory cortex activity	EEG recorded during anterior translation of the tibia on the femur	ACLR limb exhibited higher activity of somatosensory cortex during early loading of the knee capsule as compared to uninjured limb	EEG
No significant difference	Courtney et al (Courtney et al., 2019) Comparative study	ACLR (n=20) 27 ± 6 yrs Healthy controls (n=20) 27 ± 5.5	65 ± 47	Vibration perception threshold testing at distal and local (knee) sites of the leg	Local sites were medial femoral condyle, lateral femoral condyle and tibial tuberosity. Distal sites were medial malleolus and lateral malleolus.	No significant difference in vibration perception threshold at sites distal to the knee	Biothesiometer

	Blackburn et al (Blackburn et al., 2020) Cohort study	ACLR (n=72) 21 ± 3 yrs	27 ± 16	Vibration perception threshold testing at distal and local (knee) sites of the leg	Sidelying position. Local sites were medial femoral condyle and lateral femoral condyle. Distal sties were medial malleolus, lateral malleolus and first metatarsal	No difference between ACLR limb and uninjured limb at distal sites	Biothesiometer
Proprioception **JPS**							
Significant reduction in function (p<0.05)	Relph et al (Relph et al., 2014b) Systematic review with meta-analysis	Fives studies compared 170 participants' ACLR limb to their uninjured limb	mixed	mixed	Various JPS methods	The pooled standard mean difference angle of error of 0.52°, with the uninjured limb performing better than ACLR limb	Mixed
	Angoules et al (Angoules et al., 2011b) Randomised controlled trial	ACLR (n=40) 31 yrs	3	Active angle reproduction in custom built apparatus	Active angle reproduction	Significantly greater JPS error in the ACLR limb as compared to the uninjured limb at 15° (ACLR= 3.9 ± 1.5° and uninjured limb= 2 ± 0.9°), 45° (ACLR= 3.7 ± 1.5° and uninjured limb= 2.2 ± 0.9°) and 75° (ACLR= 3.7 ± 1.2° and uninjured limb= 2.5 ± 1.1°)	Custom built apparatus

	Fremerey et al (Fremerey et al., 2000) Comparative study	ACLR (n=20) 28.4 ± 4.4 yrs Healthy controls (n=20) 26.4 ± 4.8 yrs	6 and 44.4 ± 3.6	Active angle reproduction in custom built apparatus	Active angle reproduction	ACLR limb significantly greater JPS error than uninjured limb in mid-range at 6 and 12 months (ACLR= 2.8 ± 1.2° and uninjured side= 1.9 ± 0.7°)	Custom built apparatus
	Fischer-Rasmussen et al (Fischer-Rasmussen and Jensen, 2000) Comparative study	ACL (n=18) 27 ± 5 yrs Healthy controls (n=20) 27 ± 4 yrs	unclear	Active angle reproduction in custom built apparatus	Supine knee extension/flexion	ACLR limb demonstrated greater JPs error than uninjured limb when measured at 60° knee flexion (ACLR=3.5 ± 1.4° and uninjured limb= 2.7 ± 1.4°)	Custom built apparatus utilising goniometer
	Buyukafsar et al (Büyükafşar et al., 2020) Comparative study	ACLR (n=16) 33 ± 7.8 yrs Healthy controls (n=16) 32.4 ± 4.4 yrs	52.2 ± 26.8	Active angle reproduction utilising digital inclinometer	Single leg squat	ACLR limb demonstrated greater JPS error than uninjured limb when measured at 30° (ACLR= 3.3 ± 0.3° and uninjured limb= 3.1 ± 0.2°) and 60° (ACLR= 5.2 ± 0.3° and uninjured limb= 5 ± 0.2°) knee flexion	Digital inclinometer
	Hoshiba et al (Hoshiba et al., 2020) Comparative study	ACLR (n=11) 20.5 ± 1.2 yrs Healthy controls (n=12) 22.8 ± 1.6 yrs	6	Active angle reproduction task-matching contralateral limb angle utilising electrogoniometer	Seated knee extension/flexion	Significantly greater angular error during limb matching task when the ACLR limb was used for the reference position ($F_{1,10}$= 11.6	Electrogoniometer

	Anders et al (Anders et al., 2008) Cohort study	ACLR (n=45) 31 yrs	36	Active and passive angle reproduction utilising electrogoniometer	Seated knee extension/flexion	Greater JPS error in the ACLR limb (ACLR limb= 2.78° vs contralateral limb= 2.06°)	Electrogoniometer
	Bonfim et al (Bonfim et al., 2003) Comparative study	ACLR (n=10) 24.4 ± 4.5 yrs Healthy Controls (n=10) 24.4 ± 3.0yrs	18	Passive angle reproduction in continuous passive motion device	Supine knee extension/flexion	ACLR limb demonstrated significantly greater JPS error when measured at 0°, 15°, 30°, 45° and 60°	Continuous passive motion device
	Relph et al (Relph and Herrington, 2016b) Comparative study	ACLR (n=10) 22.4 ± 3.8 yrs Healthy controls (n=10) 22.1 ± 4.1	17.9 ± 4.7	Active angle reproduction utilising electrogoniometer	Seated knee extension/flexion	ACLR limb demonstrated significantly greater JPS error than the uninjured limb (ACLR= 8.1 ± 1.2° and uninjured limb= 3.5 ± 0.7°)	Electrogoniometer
	Ghaderi et al (Ghaderi et al., 2020) Longitudinal study	ACLR- Group 1 (n=12) 26.9 ± 4.1 yrs ACLR- Group 2 (n=12) 27.2 ± 3.4 yrs	Group 1= 7.5 ± 1.4 Group 2= 7.8 ± 1.7	Passive angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	Both ACLR groups demonstrated greater JPS error in the ACLR limb as compared to the uninjured limb (ACLR= 6.3 ± 2.8° and uninjured limb= 4.4 ± 1°)	Isokinetic dynamometer

	Fremerey et al (Fremerey et al., 2001) Longitudinal study	ACLR (n=29) 26.6 yrs	3	Passive angle reproduction utilising custom built apparatus	Seated knee extension/flexion	ACLR demonstrated significantly greater JPS error than uninjured limb in all 3 positions: extended, flexed and mid-range	Custom built apparatus
			6 and 46.8 ± 4.8			ACLR demonstrated significantly greater JPS error than uninjured limb in mid-range position	
	Silva et al (Silva et al., 2012) Comparative study	ACLR (n=7) 26.6 ± 4.8 yrs Healthy controls (n=9) 26.8 ± 3.8 yrs	5	Active angle reproduction with image- calculated angulation software	Seated knee extension/flexion	ACLR limb demonstrated significantly greater JPS error as compared to the uninjured limb (ACLR= 6 ± 2.7° and uninjured limb= 2.2± 2.7°)	Image calculated angulation software
	Jureviciene et al (Jurevičienė et al., 2012) Longitudinal study	ACLR (n=15) 33.7 ± 2.5 yrs	4	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	ACLR limb demonstrated significantly greater JPS error than the uninjured limb in both flexion (30.8% increase) and extension (40.4% increase) directions	Isokinetic dynamometer
			5			ACLR limb demonstrated significantly greater JPS error than the uninjured limb in both flexion (21.1% increase) and extension (30.8% increase) directions	

No significant difference	Risberg et al (Risberg et al., 2007b) Randomised controlled trial	ACLR (n=47) Demographic data limited as 47 out of 74 completed the proprioceptive data	6	Threshold to detect motion in isokinetic dynamometer	Seated knee extension/flexion	No difference in the involved or uninvolved leg	Isokinetic dynamometer
	Kaya et al (Kaya et al., 2019) Longitudinal study	ACLR (n=32) 29.4 ± 9.7 yrs	4 and 5	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference between ACLR and uninjured side	Isokinetic dynamometer
	Zult et al (Zult et al., 2018) Randomised controlled trial	ACLR (n=43) 28 ± 9.5	1.25, 3 and 4.5	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference between limbs of experimental groups at angles 15°, 30°, 45° and 60°	Isokinetic dynamometer
	Fischer-Rasmussen et al (Fischer-Rasmussen and Jensen, 2000) Comparative study	ACLR (n=18) 27 ± 5 yrs Healthy controls (n=20) 27 ± 4 yrs	unclear	Active angle reproduction in custom built apparatus	Supine knee extension/flexion	No difference between limbs when measuring the movement starting from 0° (ACLR limb= 3.10 ± 1.54° vs control limb= 3.02 ± 0.93°)	Custom built apparatus utilising goniometer

	Ozenci et al (Ozenci et al., 2007) Retrospective cohort study	ACLR- utilising autograft (n=20) 29.5 ± 6.9 yrs ACLR- utilising allograft (n=20) 30.2 ± 4.6 yrs Healthy controls (n=20) 29 ± 5.4 yrs	ACLR autograft= 16.5 ± 5.5 ACLR allograft= 25.6 ± 13	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference between ACLR and uninjured limbs (ACLR autograft= 4.75 ± 2.15° and uninjured limb= 4.54 ± 2°) (ACLR allograft= 4.6 ± 1.9° and uninjured limb= 4.5 ± 1.6°)	Isokinetic dynamometer
		ACLR- utilising allograft (n=20) Healthy controls (n=20)	25.6 ± 3.6	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference between ACLR and control limbs (ACLR= 4.58 ± 1.87° vs controls= 4.54 ± 1.34°)	Isokinetic dynamometer
	Mir et al (Mir et al., 2008) Comparative study	ACLR (n=12) 23 ± 4.8 yrs Healthy controls (n=12) 22 ± 4.4 yrs	11	Active angle reproduction utilising image calculated angulation	Single leg squat	No difference between limbs when moving from flexion to extension (ACLR limb= 3.65 ± 2.39° vs uninjured limb 4.28 ± 2.08°) No difference between limbs when moving from extension to flexion (ACLR limb= 3.77 ± 2.04° vs uninjured limb 4.13 ± 2.51°)	Image calculated angulation with auto CAD
	Angoules et al (Angoules et al., 2011b) Randomised controlled trial	ACLR (n=40) 31 yrs	6 and 12	Active angle reproduction in custom built apparatus	Active angle reproduction	No difference in JPS at 15°, 45° and 75°	Custom built apparatus

	Nagai et al (Nagai et al., 2018) Randomised controlled trial	ACLR (n=14) 19.8 ± 6.9 yrs Healthy controls (n=14) 21.6 ± 4.1 yrs	9.9 ± 2.1	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference in JPS performance at 15°, 45° and 75°	Isokinetic dynamometer
	Buyukafsar et al (Büyükafşar et al., 2020) Comparative study	ACLR (n=16) 33 ± 7.8 yrs Healthy controls (n=16) 32.4 ± 4.4 yrs	52.2 ± 26.8	Active angle reproduction utilising digital inclinometer	Single leg squat	No difference between ACLR limb and uninjured limb when measured at 15° flexion	Digital inclinometer
	Furlanetto et al (Furlanetto et al., 2016) Comparative study	ACLR (n=20) 29.2 ± 8.1 yrs Healthy controls (n=20) 27.8 ± 4.0	6	Active angle reproduction utilising image calculated angulation software	Prone knee flexion/extension	No difference between ACLR limb and uninjured limb when measured at 40° and 90°	Image calculated angulation software
	Blackburn et al (Blackburn et al., 2020) Cohort study	ACLR (n=72) 21 ± 3 yrs	27 ± 16	Active angle reproduction utilising electrogoniometer	Single leg squat performed on reclined platform	No difference in JPS between the ACLR limb and uninjured when measured at 20°, 25° and 30°	electrogoniometer
	Karasel et al (Karasel et al., 2010) Cohort study	ACLR (n=38) 27.6 ± 6.4 yrs	16.2 ± 9.8	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference in JPS between ACLR limb and uninjured limb when measured at 5°, 20° and 40°	Isokinetic dynamometer

	Co et al (Co et al., 1993) Comparative study	ACLR (n=10) 27 yrs Healthy controls (n=10) 24 yrs	31.6	Passive angle reproduction utilising custom built apparatus	Seated knee extension/flexion	No difference between limbs	Custom built apparatus
	Hoshiba et al (Hoshiba et al., 2020) Comparative study	ACLR (n=11) 20.5± 1.2 yrs Healthy controls (n=12) 22.8 ± 1.6 yrs	6 and 12	Active angle reproduction utilising electrogoniometer	Seated knee extension/flexion	No difference between limbs	Electrogoniometer
			6 and 12	Limb matching task utilising electrogoniometer		No difference in performance when uninjured limb was used as reference limb	Electrogoniometer
	Anders et al (Anders et al., 2008) Cohort study	ACLR (n=45) 31 yrs	36	Active and passive angle reproduction utilising electrogoniometer	Seated knee extension/flexion	No difference between limbs both actively and passively	electrogoniometer
				Active and passive angle reproduction utilising electrogoniometer	Supine knee extension/flexion	No difference between limbs both actively and passively	
				Active angle reproduction utilising electrogoniometer	Single leg squat	No difference between limbs	
	Suner Keklik et al (Suner Keklik et al., 2021) Comparative study	ACLR (n=34) 29.2 ± 8.2 yrs Healthy controls (n=31) 27.4 ± 5.7 yrs	24 ± 15	Active angle reproduction utilising electrogoniometer	Single leg squat	No difference in JPS performance between limbs (ACLR limb= 4.4 ± 2.6°, uninjured limb= 4.2 ± 2.7°)	Electrogoniometer

	Hopper et al (Hopper et al., 2003) Cohort study	ACLR (n=9) 29.3 yrs	12 to 16	Active angle reproduction utilising image captured angulation software	Single leg squat	No difference between limbs during both flexion and extension movements	Image captured angulation software
	Dvir et al (Dvir et al., 1988) Cohort study	ACLR (n=25) 17 to 31 yrs	12.2	Active angle reproduction utilising custom built apparatus	Seated knee extension/flexion	No difference between limbs during both active and passive testing modes	Custom built apparatus
	Fremerey et al (Fremerey et al., 2001) Longitudinal study	ACLR (n=29) 26.6 yrs	6 and 46.8 ± 4.8	Passive angle reproduction utilising custom built apparatus	Seated knee extension/flexion	No difference between limbs when measured between 0-20° and 80-100°	Custom built apparatus
	Reider et al (Reider et al., 2003) Comparative study	ACLR (n=26) 25 yrs Healthy controls (n=26) 25 yrs	0.75, 1.5 and 3	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference between limbs	Isokinetic dynamometer
Significant increase in function (p<0.05)	Reider et al (Reider et al., 2003) Comparative study	ACLR (n=26) 25 yrs Healthy controls (n=26) 25 yrs	6	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	ACLR limb demonstrated less JPS error than uninjured limb at 6 months (ACLR limb= 5.7° and uninjured limb= 6.9°	Isokinetic dynamometer

	Dvir et al (Dvir et al., 1988) Cohort Study	ACLR (n=25) Age range 17-37	12.2	Passive angle reproduction utilising electrogoniometer	Seated knee extension/flexion	ACLR limb demonstrated less JPS error than uninjured limb. Difference between legs 1.8 ± 1.2°	Electrogoniometer
Kinaesthesia TTDPM							
Significant reduction in function (p<0.05)	Valeriani et al (Valeriani et al., 1999) Cohort study	ACLR (n=7) Unclear age profile	Atleast 24	TTDPM utilising custom built apparatus between 30° and 40°	Seated knee extension/flexion	ACLR limb significantly reduced performance as compared to uninjured limb.	Custom built apparatus
	Fischer-Rasmussen et al (Fischer-Rasmussen and Jensen, 2000)	ACLR (n=18) 27 ± 5 yrs Healthy controls (n=20) 27 ± 4 yrs	unclear	TTDPM utilising custom built apparatus at 20° knee flexion	Supine knee extension/flexion	ACLR limb significantly reduced performance as compared to the uninjured limb (ACLR limb= 1.4 ± 0.5° and uninjured limb= 1.3 ± 0.5°)	Custom built apparatus
	Courtney et al (Courtney et al., 2019) Comparative study	ACLR (n=20) 27 ± 6 yrs Healthy controls (n=20) 27 ± 5.5	65 ± 47	TTDPM utilising custom built apparatus at 45° knee flexion	Supine knee extension/flexion	ACLR limb significantly reduced performance as compared to the uninjured limb (ACLR limb= 4.8 ± 0.7° and uninjured limb= 3.4 ± 1.2°)	Custom built apparatus

	Laboute et al (Laboute et al., 2019) Cohort study	ACLR Group 1 (n=32) 24.9 ± 5.9 yrs Group 2 (n=32) 24.9 ± 5.3 yrs Healthy controls (n=32) 26.2 ± 6.2 yrs	Group 1= 1 Group 2= 5.5	TTDPM utilising isokinetic dynamometer at 0° and 15° knee flexion	Seated knee extension/flexion	Group 1- ACLR limb significantly reduced function as compared to uninjured limb (ACLR limb= 1.2 ± 0.5° and uninjured limb= 0.95 ± 0.3°)	Isokinetic dynamometer
	Co et al (Co et al., 1993) Comparative study	ACLR (n=10) 27 yrs Healthy controls (n=10) 24 yrs	31.6	TTDPM utilising custom built apparatus	Seated knee extension/flexion	ACLR limb significantly reduced performance as compared to uninjured limb (ACLR limb= 1.3 ± 0.8° and uninjured limb= 1.2 ± 0.4°)	Custom built apparatus
	MacDonald et al (MacDonald et al., 1996) Comparative study	ACLR Group 1 (n=8) 25.8 yrs Group 2 (n=8) 26.4 yrs Healthy controls (n=6) 30 yrs	66.8	TTDPM utilising custom built apparatus between 30° and 40°	Seated knee extension/flexion	Group 1- ACLR limb performed worse than uninjured limb (ACLR limb= 0.8 ± 0.2° and uninjured limb= 0.7 ± 0.2°) Group 2- ACLR limb performed worse than uninjured limb (ACLR limb= 0.8 ± 0.2° and uninjured limb= 0.6 ± 0.2°)	Custom built apparatus

	Bonfim et al (Bonfim et al., 2003) Comparative study	ACLR (n=10) 24.4 ± 4.5 yrs Healthy Controls (n=10) 24.4 ± 3.0yrs	18	TTDPM utilising continuous passive motion device between 0°, 15°, 30°, 45° and 60°	Supine knee extension/flexion	ACLR limb demonstrated significantly higher thresholds to detect motion both in the extension and flexion direction as compared to the uninjured limb	Continuous passive motion device
	Nagai et al (Nagai et al., 2013) Comparative study	ACLR (n=11) 23.1 ± 4.8 yrs Healthy controls (n=11) 22.5 ± 3.2 yrs	Atleast 12	TTDPM utilising isokinetic dynamometer	Seated knee flexion/extension, internal rotation and external rotation	ACLR limb demonstrated significantly higher threshold to detect motion into internal rotation when start position was externally rotation knee (ACLR limb= 1.9 ± 1.1° and uninjured limb= 1.2 ± 0.8°	isokinetic dynamometer
	Angoules et al (Angoules et al., 2011b) Randomised controlled trial	ACLR (n=40) 31 yrs	3	TTDPM utilising isokinetic dynamometer at 15 ° and 45° knee flexion	Seated knee extension/flexion	ACLR limb demonstrated higher thresholds to detect motion at 15° when moving into extension (ACLR limb= 1.8 ± 0.7° and uninjured limb= 1.4 ± 1°) and into flexion (ACLR limb= 1.9 ± 0.6° and uninjured limb= 1.2 ± 1°)	Isokinetic dynamometer
No significant difference	Relph et al (Relph et al., 2014b) Systematic review with meta-analysis	ACLR 71 ACLR limbs 71 uninjured limbs	mixed	mixed	Various TTDPM methods	No difference in performance between limbs	Mixed methods

	Ozenci et al (Ozenci et al., 2007) Retrospective cohort study	ACLR- utilising autograft (n=20) ACLR- utilising allograft (n=20) 30.2 ± 4.6 yrs Healthy controls (n=20)	Autograft ACLR= 16.5 ± 5.5 Allograft ACLR= 25.6 ± 13	TTDPM utilising isokinetic dynamometer at 15° knee flexion	Seated knee extension/flexion	No difference between ACLR limb and uninjured limb for both autograft and allograft groups	Isokinetic dynamometer
	Angoules et al (Angoules et al., 2011b) Randomised controlled trial	ACLR (n=40) 31 yrs	6 and 12	TTDPM utilising isokinetic dynamometer at 15 ° and 45° knee flexion	Seated knee extension/flexion	No difference in TTDPM performance at 15° and 45° when moving into both flexion and extension	Isokinetic dynamometer
	Risberg et al (Risberg et al., 1999) Cohort study	ACLR (n=20) 35 yrs Healthy controls (n=10) 33 yrs	24	TTDPM utilising custom built apparatus	Seated knee extension/flexion	No difference between limbs	Custom built apparatus
	Laboute et al (Laboute et al., 2019) Cohort study	ACLR Group 1 (n=32) 24.9 ± 5.9 yrs Group 2 (n=32) 24.9 ± 5.3 yrs Healthy controls (n=32) 26.2 ± 6.2 yrs	Group 1= 1 Group 2= 5.5	TTDPM utilising isokinetic dynamometer at 0° and 15° knee flexion	Seated knee extension/flexion	No difference in TTDPM performance between limbs in group 2	Isokinetic dynamometer

	Ordahan et al (Ordahan et al., 2015) Comparative study	ACLR (n=20) 28.7 ± 8.5 yrs Healthy controls (n=16) 31.1 ± 8.4 yrs	6	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference between ACLR and uninjured limbs when JPS performance measured at 30° and 70°	Isokinetic dynamometer
	Nagai et al (Nagai et al., 2013) Comparative study	ACLR (n=11) 23.1 ± 4.8 yrs Healthy controls (n=11) 22.5 ± 3.2 yrs	Atleast 12	TTDPM utilising isokinetic dynamometer	Seated knee flexion/extension, internal rotation and external rotation	No difference between limbs during knee flexion, extension, internal rotation or external rotation	isokinetic dynamometer
	Shidahara et al (Shidahara et al., 2011) Cohort study	ACLR (n=31) 22.2 ± 9.7	3, 6 and 12	TTDPM utilising isokinetic dynamometer at 15° and 45° knee flexion	Seated knee extension/flexion	No difference in TTDPM performance between limbs at any time point	Isokinetic dynamometer
	Muaidi et al (Muaidi et al., 2009) Comparative study	ACLR (n=20) 30.4 ± 1.4 Healthy controls (n=20) 29.5 ± 1.8	3 and 6	TTDPM utilising custom made apparatus with knee at 90°	Seated knee rotation 0° to 45° in both directions	No significant difference between limbs at either time point	Custom made apparatus
	Reider et al (Reider et al., 2003) Comparative study	ACLR (n=26) 25 yrs Healthy controls (n=26) 25 yrs	0.75, 1.5, 3 and 6	TTDPM utilising isokinetic dynamometer at 15° knee flexion	Seated knee extension/flexion	No difference in TTDPM performance between limbs at any time point	Isokinetic dynamometer

Vibration							
Significant reduction in function (p<0.05)	Courtney et al (Courtney et al., 2019) Comparative study	ACLR (n=20) 27 ± 6 yrs Healthy controls (n=20) 27 ± 5.5	65 ± 47	Vibration perception threshold testing over malleoli (medial and lateral), femoral epicondyles (medial and lateral) and tibial tuberosity	Unclear on patient position	Significantly higher vibration thresholds in the ACLR limb as compared to the uninjured limb at the medial femoral epicondyle, lateral femoral epicondyle and tibial tuberosity	Biothesiometer
No significant difference	Courtney et al (Courtney et al., 2019) Comparative study	ACLR (n=20) 27 ± 6 yrs Healthy controls (n=20) 27 ± 5.5	65 ± 47	Vibration perception threshold testing over malleoli (medial and lateral), femoral epicondyles (medial and lateral) and tibial tuberosity	Unclear on patient position	No difference between limbs when measuring at medial and lateral malleoli	Biothesiometer
	Blackburn et al (Blackburn et al., 2020) Cohort study	ACLR (n=72) 21 ± 3 yrs	27 ± 16	Vibration perception threshold testing over malleoli (medial and lateral) and femoral epicondyles (medial and lateral)	Sidelying position	No difference between limbs at any of the test locations	Biothesiometer

TTDPM= threshold to detect passive motion, ACLR= anterior cruciate ligament reconstruction, JPS= joint position sense, MRI= magnetic resonance imaging, EEG= electroencephalogram, BPTB= bone patellar tendon bone, HS= hamstring

Table D2. Summary table of tables examining between group differences in ACLR cohort and healthy controls (ACLR limb versus healthy control limb)

Level of somatosensory system	Authors	Participant information	Time from surgery (months)	Outcome measure used	Task	Results	Testing tool
Central processing							
Significant reduction in function (p<0.05)	Grooms et al (Grooms et al., 2017) Comparative study	ACLR (n= 15) 21.7 ± 2.7 yrs Healthy Controls (n= 15) 23.2 ± 3.5 yrs	38.1 ± 27.2	Functional brain MRI during movement task	Supine knee flexion/extension	ACLR cohort exhibited higher activity of the ipsilateral secondary somatosensory cortex (mean z-value= 5.6) and primary motor cortex (mean z-value= 5.1)	Functional brain MRI
	Baumeister et al (Baumeister et al., 2008) Comparative study	ACLR (n=10) 27 ± 5 Healthy controls (n=12) 25 ± 3	12.5 ± 4.6	EEG during joint position sense test	Seated knee extension/flexion	ACLR patients had significantly increased frontal theta power and parietal Alpha-2 power than healthy controls during the JPS task. These two areas are related to executive function such as attention during motor tasks	EEG

	An et al (An et al., 2019) Comparative study	ACLR (n=17) 26.9 ± 5.6 yrs Healthy control (n=17) 22.3 ± 3.8 yrs	41.8 ± 24.7	EEG recording of somatosensory cortex activity	EEG recorded during anterior translation of the tibia on the femur	ACLR limb exhibited higher activity of somatosensory cortex during early and late loading of the knee capsule as compared to healthy controls	EEG
	Courtney et al (Courtney et al., 2019) Comparative study	ACLR (n=20) 27 ± 6 yrs Healthy controls (n=20) 27 ± 5.5	65 ± 47	Vibration perception threshold testing at distal and local (knee) sites of the leg	Local sites were medial femoral condyle, lateral femoral condyle and tibial tuberosity. Distal sites were medial malleolus and lateral malleolus.	The ACLR limb and uninjured limb demonstrated significantly hight vibration perception thresholds than healthy controls (ACLR limb medial malleolus= 13.8 ± 6.6 and lateral malleolus= 14 ± 4.3. Healthy controls medial malleolus= 11 ± 2 and lateral malleolus= 11 ± 3)	Biothesiometer
	Hoch et al (Hoch et al., 2017) Comparative study	ACLR (n=15) 22 ± 5 Healthy controls (n=15) 21 ± 6	48	Cutaneous detection testing with Semmes-Weinstein monofilament kit. Tested over medial and lateral malleoli, base of 5th metatarsal and plantar surface of 1st metatarsal	prone	ACLR group had higher thresholds to detect cutaneous stimuli than healthy controls at the 1st metatarsal (median and interquartile range reported. ACLR=3.8 ± 0.3 and healthy control= 3.6 ± 1.7) and medial malleolus (median and interquartile range reported. ACLR= 4.3 ± 0.9 and healthy controls= 4.1 ± 0.5)	Cutaneous detection testing with Semmes-Weinstein monofilament kit

Proprioception JPS							
Significant reduction in function (p<0.05)	Relph et al (Relph et al., 2014b) Systematic review with meta-analysis	Four studies compared ACLR limb (n=140) to healthy control limbs (n=104)	mixed	mixed	Various JPS methods	The pooled standard mean difference of the mean angle of error was 0.35°, with the healthy control limb performing better	Mixed
	Barrett et al (Barrett, 1991b) Comparative study	ACLR (n=45) 26.4 yrs Healthy controls (n=20) Age of cohort unclear	38.4	Active angle reproduction in custom built apparatus	Seated knee extension/flexion	ACLR limb greater JPS error as compared to healthy control knees	Custom built apparatus
	Fischer-Rasmussen et al (Fischer-Rasmussen and Jensen, 2000)	ACL (n=18) 27 ± 5 yrs Healthy controls (n=20) 27 ± 4 yrs	unclear	Active angle reproduction in custom built apparatus	Supine knee extension/flexion	Significant difference between ACLR group and healthy control group with regards to JPS error when moving into extension from 60°	Custom built apparatus utilising goniometer
	Buyukafsar et al (Büyükafşar et al., 2020) Comparative study	ACLR (n=16) 33 ± 7.8 yrs Healthy controls (n=16) 32.4 ± 4.4 yrs	52.2 ± 26.8	Active angle reproduction utilising electrogoniometer	Single leg squat	Greater JPS error in ACLR limb as compared to healthy control limb when knee flexed to 60°. (ACLR= 5.3 ± 0.3° and healthy control= 4.9 ± 0.3°)	Electrogoniometer

	Baumeister et al (Baumeister et al., 2008) Comparative study	ACLR (n=10) 27 ± 5 Healthy controls (n=12) 25 ± 3	12.5 ± 4.6	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	ACLR patients had significantly greater JPS error scores than healthy controls	Isokinetic dynamometer
	San Martin-Mohr et al (San Martín-Mohr et al., 2018) Comparative study	ACLR with BPTB (n=30) 25.8 ± 4.5 ACLR with HS (n=26) 26.6 ± 5.7 yrs Healthy controls (n=27) 24.3 ± 3.3	ACLR with BPTB= 7.8 ± 2.3 ACLR with HS= 8.9 ± 2.3	Active angle reproduction utilising electrogoniometer	Sesated knee extension/flexion	Both ACLR groups demonstrated significantly greater JPS error than healthy controls when measured through a range of 0-30° (ACLR BPTB= 3.5 ± 1.9°, ACLR HS= 3.2 ± 2.7° and healthy control= 2.2 ± 1.2°	electrogoniometer
	Bonfim et al (Bonfim et al., 2003) Comparative study	ACLR (n=10) 24.4 ± 4.5 yrs Healthy Controls (n=10) 24.4 ± 3 yrs	18	Passive angle reproduction in continuous passive motion device	Supine knee extension/flexion	ACLR group demonstrated significantly greater JPS error than healthy controls ($F_{1,18}$= 12.4, $p<0.05$)	Continuous passive motion device

	Guney-Deniz et al (Guney-Deniz et al., 2020) Comparative study	ACLR- with HS (n=24) 26.7 ± 4.6 yrs ACLR with TAA (n=21) 26.4 ± 5.5 yrs ACLR with QT (n=22) 27.8 ± 2.8 yrs Healthy controls (n=20) 28.7 ± 3.1 yrs	ACLR- with HS= 13.3 ± 1.8 ACLR with TAA= 13.1 ± 1.9 ACLR with QT= 13.5 ± 2.1	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	All 3 ACLR groups had significantly greater JPS errors when measured at the 15° target angle than healthy controls ($F_{3.86}$= 24.56, p<0.001)	Isokinetic dynamometer
	Zhou et al (Zhou et al., 2008) Comparative study	ACLR (n=36) 26 ± 5.8 yrs Healthy controls (n=13) 26.4 ± 3.9	6.3 ± 0.4	Passive angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	ACLR limb demonstrated greater JPS errors than healthy controls (ACLR= 5.6 ± 2.6° and healthy control= 4.3 ± 1.1°)	Isokinetic dynamometer
	Goetschius et al (Goetschius et al., 2013) Comparative study	ACLR (n=20) 25.5 ± 5.5 yrs Healthy controls (n=20) 24.6 ± 5 yrs	60 ± 51.6	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	Significantly greater JPS error in ACLR limb as compared to healthy controls when measured at 45° (ACLR= 5.2 ± 4.4° and healthy controls= 3.0 ± 3.3°)	Isokinetic dynamometer

	Suner Keklik et al (Suner Keklik et al., 2021) Comparative study	ACLR (n=34) 29.2 ± 8.2 yrs Healthy controls (n=31) 27.4 ± 5.7 yrs	24 ± 15	Active angle reproduction utilising electrogoniometer	Single leg squat	Both limbs of ACLR patients demonstrated greater JPS errors than control group (ACLR limb= 4.4 ± 2.6°, uninjured limb of ACLR= 4.2 ± 2.7° and healthy controls= 2 ± 1.6°)	Electrogoniometer
	Relph et al (Relph and Herrington, 2016b) Comparative study	ACLR (n=10) 22.4 ± 3.8 yrs Healthy controls (n=10) 22.1 ± 4.1	17.9 ± 4.7	Active angle reproduction utilising image captured angulation software	Seated knee extension/flexion	ACLR limb demonstrated significantly greater JPS error than healthy controls (ACLR= 8.1 ± 1.2° and healthy controls= 3.1 ± 1.8°)	Image captured angulation software
	Silva et al (Silva et al., 2012) Comparative study	ACLR (n=7) 26.6 ± 4.8 yrs Healthy controls (n=9) 26.8 ± 3.8 yrs	5	Active angle reproduction with image calculated angulation software	Seated knee extension/flexion	ACLR limb demonstrated significantly greater JPS error than healthy controls (ACLR= 6 ± 2.7° and healthy controls= 2.2 ± 1.3°)	Image calculated angulation software

No significant difference	Ozenci et al (Ozenci et al., 2007) Retrospective cohort study	ACLR- utilising autograft (n=20) 29.5 ± 6.9 yrs ACLR- utilising allograft (n=20) 30.2 ± 4.6 yrs Healthy controls (n=20) 29 ± 5.4 yrs	ACLR autograft= 16.5 ± 5.5 ACLR allograft= 25.6 ± 13	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference between ACLR and healthy control limbs (ACLR autograft= 4.75 ± 2.15°, ACLR allograft= 4.6 ± 1.9° and uninjured limb= 4.54 ± 1.3°)	Isokinetic dynamometer
	Ordahan et al (Ordahan et al., 2015) Comparative study	ACLR (n=20) 28.7 ± 8.5 yrs Healthy controls (n=16) 31.1 ± 8.4 yrs	6	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference between ACLR and healthy control limbs when JPS performance measured at 30° and 70°	Isokinetic dynamometer
	Fischer-Rasmussen et al (Fischer-Rasmussen and Jensen, 2000)	ACL (n=18) 27 ± 5 yrs Healthy controls (n=20) 27 ± 4 yrs	unclear	Active angle reproduction in custom built apparatus	Supine knee extension/flexion	No difference between ACLR and healthy controls during JPS performance when starting from 0°	Custom built apparatus utilising goniometer
	Mir et al (Mir et al., 2008) Comparative study	ACLR (n=12) 23 ± 4.8 yrs Healthy controls (n=12) 22 ± 4.4 yrs	11	Active angle reproduction utilising image calculated angulation software	Single leg squat	No difference between JPS performance between ACLR and healthy controls	Image calculated angulation software

	San Martin-Mohr et al (San Martín-Mohr et al., 2018) Comparative study	ACLR with BPTB (n=30) 25.8 ± 4.5 ACLR with HS (n=26) 26.6 ± 5.7 yrs Healthy controls (n=27) 24.3 ± 3.3 yrs	ACLR with BPTB= 7.8 ± 2.3 ACLR with HS= 8.9 ± 2.3	Active angle reproduction utilising electrogoniometer	Seated knee extension/flexion	No difference between ACLR groups and healthy controls when measured at 30-60° and 60-90°	electrogoniometer
	Armitano-Lago et al (Armitano-Lago et al., 2020) Comparative study	ACLR (n=16) 29.3 ± 6.9 yrs Healthy controls (n=16) 28.9 ± 6.2 yrs	106.9 ± 71.6	Active angle reproduction during a limb matching task. Utilising goniometer	Seated knee extension/flexion	No difference between ACLR limb and dominant limb of healthy controls (ACLR= 0.9 ± 0.8° and healthy controls= 1 ± 0.8°)	Goniometer
	Buyukafsar et al (Büyükafşar et al., 2020) Comparative study	ACLR (n=16) 33 ± 7.8 yrs Healthy controls (n=16) 32.4 ± 4.4 yrs	52.2 ± 26.8	Active angle reproduction utilising digital inclinometer	Single leg squat	No difference between ACLR limb and healthy controls when measured at 15° and 30° knee flexion	Digital inclinometer
	Furlanetto et al (Furlanetto et al., 2016) Comparative study	ACLR (n=20) 29.2 ± 8.1 yrs Healthy controls (n=20) 27.8 ± 4.0	6	Active angle reproduction utilising image calculated angulation software	Prone knee flexion/extension	No difference between ACLR limbs and heathy controls when measured at 40° and 90°	Image calculated angulation software

	Hoshiba et al (Hoshiba et al., 2020) Comparative study	ACLR (n=11) 20.5± 1.2 yrs Healthy controls (n=12) 22.8 ± 1.6 yrs	6	Active angle reproduction utilising electrogoniometer	Seated knee extension/flexion	No difference between ACLR limb and healthy control limb	Electrogoniometer
	Zandiyeh et al (Zandiyeh et al., 2019) Comparative study	ACLR (n=19) 25 ± 5yrs Healthy controls (n=28) 24 ± 4 yrs	3	Passive angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference in JPS performance between ACLR and healthy controls	Isokinetic dynamometer
	Co et al (Co et al., 1993) Comparative study	ACLR (n=10) 27 yrs Healthy controls (n=10) 24 yrs	31.6	Passive angle reproduction utilising custom built apparatus	Seated knee extension/flexion	No difference between ACLR and healthy control limbs	Custom built apparatus

	Guney-Deniz et al (Guney-Deniz et al., 2020) Comparative study	ACLR- with HS (n=24) 26.7 ± 4.6 yrs ACLR with TAA (n=21) 26.4 ± 5.5 yrs ACLR with QT (n=22) 27.8 ± 2.8 yrs Healthy controls (n=20) 28.7 ± 3.1 yrs	ACLR- with HS= 13.3 ± 1.8 ACLR with TAA= 13.1 ± 1.9 ACLR with QT= 13.5 ± 2.1	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference between ACLR groups and healthy controls when measuring JPS performance at 45° and 75°	Isokinetic dynamometer
	Goetschius et al (Goetschius et al., 2013) Comparative study	ACLR (n=20) 25.5 ± 5.5 yrs Healthy controls (n=20) 24.6 ± 5 yrs	60 ± 51.6	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference in JPS performance between ACLR and healthy controls when measured at 15°	Isokinetic dynamometer
	Littmann et al (Littmann et al., 2012) Comparative study	ACLR (n=11) 22.6 ± 2.4 yrs Healthy controls (n=20) 24 ± 1.4 yrs	43.3 ± 23.8	Active and passive angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference between ACLR and healthy controls during both active and passive angle reproduction tasks	Isokinetic dynamometer

	Chaput et al (Chaput et al., 2021a) Comparative study	ACLR (n=16) 21.5 ± 2.6 yrs Healthy controls (n=15) 22.9 ± 3 yrs	41.4 ± 33	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	No difference between ACLR and healthy controls.	Isokinetic dynamometer
	Strong et al (Strong et al., 2021) Comparative study	ACLR (n=18) 23 ± 4.4 yrs Healthy controls (unathletic) (n=23) 23.5 ± 3.4 yrs Healthy controls (athletic) (n=21) 21.2 ± 2.9 yrs	23 ± 16.4	Active angle reproduction test utilising custom made apparatus	2 testing methods: (1) supine knee extension/flexion (2) single leg squat	No difference in JPS performance during either testing method between all 3 patient groups	Custom made apparatus
Significant increase in function ($p<0.05$)	Reider et al (Reider et al., 2003) Comparative study	ACLR (n=26) 25 yrs Healthy controls (n=26) 25 yrs	6	Active angle reproduction utilising isokinetic dynamometer	Seated knee extension/flexion	ACLR limb demonstrated less JPS error than healthy controls at 6 months (ACLR limb= 5.7° and healthy controls= 7.5°	Isokinetic dynamometer

Kinaesthesia TTDPM							
Significant reduction in function (p<0.05)	Roberts et al (Roberts et al., 2000) Comparative study	ACLR (n=20) 27 yrs Healthy controls (n=19) 25 yrs	24	TTDPM utilising custom built apparatus with the knee starting at either 20° or 40° flexion.	Sidelying knee extension/flexion	ACLR limbs demonstrated higher thresholds to detect motion as compared to healthy controls when moving into extension from both 20° (ACLR= 1° and healthy control= 0.75°) and 40° (ACLR= 1° and healthy control= 0.75°). Also higher thresholds in ACLR when moving into flexion from 20° (ACLR= 2° and healthy control= 1°) and 40° (ACLR=1° and healthy control= 0.5°)	Custom built apparatus
	Relph et al (Relph et al., 2014b) Systematic review: meta-analysis	ACLR (n=71) Healthy controls (n=30)	unclear	mixed	mixed	ACLR group had mean angle error of 0.38° greater than healthy controls	mixed
	Courtney et al (Courtney et al., 2019) Comparative study	ACLR (n=20) 27 ± 6 yrs Healthy controls (n=20) 27 ± 5.5	65 ± 47	TTDPM utilising custom built apparatus at 45° knee flexion	Supine knee extension/flexion	ACLR limb significantly reduced performance as compared to healthy controls (ACLR limb= 4.8 ± 0.7° and healthy control= 2 ± 1.4°)	Custom built apparatus

	Laboute et al (Laboute et al., 2019) Cohort study	ACLR Group 1 (n=32) 24.9 ± 5.9 yrs Group 2 (n=32) 24.9 ± 5.3 yrs Healthy controls (n=32) 26.2 ± 6.2 yrs	Group 1= 1 Group 2= 5.5	TTDPM utilising isokinetic dynamometer at 0° and 15° knee flexion	Seated knee extension/flexion	ACLR limb of Group 1 and 2 demonstrated higher thresholds to detect motion than healthy controls (Group 1 ACLR limb= 1.2 ± 0.5°, Group 2 ACLR limb= 0.9 ± 0.4° and healthy controls= 0.7 ± 0.2°)	Isokinetic dynamometer
	Zandiyeh et al (Zandiyeh et al., 2019) Comparative study	ACLR (n=19) 25 ± 5yrs Healthy controls (n=28) 24 ± 4 yrs	3	TTDPM utilising isokinetic dynamometer	Seated knee extension/flexion	ACLR demonstrated greater threshold to detect motion than healthy controls by 0.3 ± 0.1°	Isokinetic dynamometer
No significant difference	Fischer-Rasmussen et al (Fischer-Rasmussen and Jensen, 2000)	ACLR (n=18) 27 ± 5 yrs Healthy controls (n=20) 27 ± 4 yrs	unclear	TTDPM utilising custom built apparatus at 20° knee flexion	Supine knee extension/flexion	No difference between ACLR limb and healthy controls	Custom built apparatus

	Ozenci et al (Ozenci et al., 2007) Retrospective cohort study	ACLR- utilising autograft (n=20) ACLR- utilising allograft (n=20) 30.2 ± 4.6 yrs Healthy controls (n=20)	Autograft ACLR= 16.5 ± 5.5 Allograft ACLR= 25.6 ± 13	TTDPM utilising isokinetic dynamometer at 15° knee flexion	Seated knee extension/flexion	No difference between ACLR limb and healthy controls	Isokinetic dynamometer
	Risberg et al (Risberg et al., 1999) Cohort study	ACLR (n=20) 35 yrs Healthy controls (n=10) 33 yrs	24	TTDPM utilising custom built apparatus	Seated knee extension/flexion	No difference between ACLR group and healthy controls	Custom built apparatus
	MacDonald et al (MacDonald et al., 1996) Comparative study	ACLR Group 1 (n=8) 25.8 yrs Group 2 (n=8) 26.4 yrs Healthy controls (n=6) 30	66.8	TTDPM utilising custom built apparatus between 30° and 40°	Seated knee extension/flexion	No difference between mean variation between ACLR groups and healthy controls	Custom built apparatus
	Bonfim et al (Bonfim et al., 2003) Comparative study	ACLR (n=10) 24.4 ± 4.5 yrs Healthy Controls (n=10) 24.4 ± 3.0yrs	18	TTDPM utilising continuous passive motion device between 0°, 15°, 30°, 45° and 60°	Supine knee extension/flexion	No difference between ACLR and healthy controls	Continuous passive motion device

	Muaidi et al (Muaidi et al., 2009) Comparative study	ACLR (n=20) 30.4 ± 1.4 Healthy controls (n=20) 29.5 ± 1.8	3 and 6	TTDPM utilising custom made apparatus with knee at 90°	Seated knee rotation 0° to 45° in both directions	No difference in TTDPM performance between ACLR and healthy control groups	Custom made apparatus
	Reider et al (Reider et al., 2003) Comparative study	ACLR (n=26) 25 yrs Healthy controls (n=26) 25 yrs	0.75, 1.5, 3 and 6	TTDPM utilising isokinetic dynamometer at 15° knee flexion	Seated knee extension/flexion	No difference in TTDPM performance between ACLR and healthy control groups	Isokinetic dynamometer
Significant increase in function (p<0.05)	Co et al (Co et al., 1993) Comparative study	ACLR (n=10) 27 yrs Healthy controls (n=10) 24 yrs	31.6	TTDPM utilising custom built apparatus	Seated knee extension/flexion	When comparing TTDPM data ACLR limb to healthy controls (limb-to-limb t test analysis) there was no significant difference. However, when the data for both limbs were pooled, then ACLR group had significantly more accurate responses than healthy controls	Custom built apparatus

Vibration							
Significant reduction in function (p<0.05)	Courtney et al (Courtney et al., 2019) Comparative study	ACLR (n=20) 27 ± 6 yrs Healthy controls (n=20) 27 ± 5.5	65 ± 47	Vibration perception threshold testing at distal and local (knee) sites of the leg	Local sites were medial femoral condyle, lateral femoral condyle and tibial tuberosity. Distal sites were medial malleolus and lateral malleolus.	Significantly higher vibration thresholds in the ACLR limb as compared to healthy controls at the medial femoral epicondyle (ACLR= 21.8 ± 8.3 and healthy control= 18.7 ± 3.5), lateral femoral epicondyle (ACLR= 21.8 ± 9.1 and healthy control= 17.9 ± 3.2) and tibial tuberosity (ACLR= 18.8 ± 8.3 and healthy control= 15 ± 4)	Biothesiometer
Light touch							
Significant reduction in function (p<0.05)	Hoch et al (Hoch et al., 2017) Comparative study	ACLR (n=15) 22 ± 5 Healthy controls (n=15) 21 ± 6	48	Cutaneous detection testing with Semmes-Weinstein monofilament kit. Tested over medial and lateral malleoli, base of 5th metatarsal and plantar surface of 1st metatarsal	prone	ACLR group had higher thresholds to detect cutaneous stimuli than healthy controls at the 1st metatarsal (median and interquartile range reported. ACLR=3.8 ± 0.3 and healthy control= 3.6 ± 1.7) and medial malleolus (median and interquartile range reported. ACLR= 4.3 ± 0.9 and healthy controls= 4.1 ± 0.5)	Cutaneous detection testing with Semmes-Weinstein monofilament kit

No significant difference	Hoch et al (Hoch et al., 2017) Comparative study	ACLR (n=15) 22 ± 5 Healthy controls (n=15) 21 ± 6	48	Cutaneous detection testing with Semmes-Weinstein monofilament kit. Tested over medial and lateral malleoli, base of 5th metatarsal and plantar surface of 1st metatarsal	prone	No difference in cutaneous detection threshold between ACLR and healthy control groups when measured at the 5th metatarsal and lateral malleolus	Cutaneous detection testing with Semmes-Weinstein monofilament kit

TTDPM= threshold to detect passive motion, ACLR= anterior cruciate ligament reconstruction, JPS= joint position sense, MRI= magnetic resonance imaging, EEG= electroencephalogram, BPTB= bone patellar tendon bone, HS= hamstring