The effectiveness of neuroplastic interventions on accelerating return to play following anterior cruciate ligament reconstruction: A Systematic Review

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Declaration

I, Amanda Hawke, declare that this Research Report is my own unaided work. It is being submitted for an MSc in Sports and Exercise Physiotherapy degree at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

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Name of candidate Signature of candidate

18th day of June 2025 in Durban

Presentations arising from this Study

None to date.

Publications arising from this Study

This review has not yet been published. This is in preparation for submission to the JBI Manual for Evidence Synthesis.

Abstract

Introduction: Anterior Cruciate Ligament (ACL) tears are debilitating activity-related orthopaedic injuries that impose a significant burden on athletes and healthcare providers. Rehabilitation following anterior cruciate ligament reconstructions (ACLR) is extensive and challenging, often resulting in high rates of reinjury, contralateral injury, and graft rupture. Research suggests that delaying return-to-play (RTP) may contribute to reducing the risk of reinjury by allowing athletes to develop novel motor strategies. This study investigated whether the integration of motor learning principles into rehabilitation could expedite recovery by targeting neuroplastic adaptations that conventional therapy may not address.

Objective: To compare the efficacy of neuroplasticity and motor learning-based interventions against traditional rehabilitation in athletes following ACLR.

Inclusion Criteria: This review included studies involving athletes of diverse ages, sexes, and ethnicities, from both contact and non-contact sports, who had undergone ACLR. The interventions focused on neuroplasticity-targeted treatment to enhance knee function compared to traditional ACLR rehabilitation. Neuroplasticity-based interventions included aspects of motor learning, sensory reweighting, visuomotor training, exercises for movement variability, and neurocognitive exercises. Outcomes assessed comprised measures of functional performance, biomechanical parameters, self-reported function, balance, and kinesiophobia. This review included randomised controlled trials (RCT's) and analytical cross-sectional studies.

Methods: A three-step search strategy identified relevant published and unpublished studies from 2013 to 2024. Reference lists of identified articles were examined for additional eligible studies. Each study underwent critical appraisal using standardised Joanna Briggs Institute (JBI) tools to ensure methodological rigour. Data on study characteristics and treatment outcomes were extracted using JBI's standardised tools. Due to substantial heterogeneity in study design, participant characteristics, intervention types, and outcome measures, results could not be statistically pooled. Instead, a narrative synthesis was performed to provide a comprehensive overview of findings.

Results: Six studies reporting outcomes of interest were critically appraised and included: five RCTs and one analytical cross-sectional study. Reported outcomes included biomechanical testing (two studies), functional performance (four studies), static standing balance and dynamic postural sway (two studies), patient-reported function (three studies), and psychological kinesiophobia status (two studies). Findings indicate that neuromuscular training with external focus of attention (EF) cueing may not significantly affect dynamic postural control, but improved biomechanics. Continuous cognitive training (CCT) appeared more effective than EF in enhancing static standing balance and dynamic postural sway. Differential training showed superior functional outcomes compared to visuomotor training, though both improved biomechanics, dynamic balance, and reduced kinesiophobia. A combined plyometric and eccentric training approach demonstrated greater improvements in isokinetic strength and psychological well-being than single-mode training. SpeedCourt training device showed notable gains in jump height and reaction time relative to the control group. Perturbation training offered no additional benefit over traditional rehabilitation focused on strengthening, agility, and secondary prevention. All six included studies assessed outcomes related to return-to-play (RTP) readiness or timelines, using functional, biomechanical, or psychological measures as proxies. However, only one study explicitly reported reinjury incidence, limiting the strength of conclusions regarding the effectiveness of neuroplastic interventions in preventing reinjury.

Conclusion: This review reveals a promising link between certain neuroplastic interventions and faster RTP timelines after ACLR. However, no study has directly measured the duration from ACLR to RTP, so conclusive evidence on neuroplastic-focused interventions' impact on RTP acceleration is limited. These findings suggest that rehabilitation programs addressing physical, neurocognitive, and psychological factors critical to safe RTP may yield better outcomes than conventional approaches. Evidence on reinjury prevention remains inconclusive due to the lack of comprehensive outcome measures capturing essential neurocognitive components for motor control. Despite high-quality evidence, the heterogeneity in study designs, intervention types, outcome measures, and population characteristics hinders definitive conclusions.

Keywords: anterior cruciate ligament reconstruction; motor learning; neuroplasticity; return to play

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List of Abbreviations

ACL	Anterior Cruciate Ligament
ACLR	Anterior Cruciate Ligament Reconstruction
RTP	Return-to-Play
CNS	Central Nervous System
PCL	Posterior Cruciate Ligament
LSI	Limb Symmetry Indices
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
JBI	Joanna Briggs Institute
SUMARI	System for the Unified Management, Assessment and Review of Information
GRADE	Grades of Recommendation, Assessment, Development, and Evaluation
ACL-SPORTS	ACL-Specialized Post-Operative Return-to-Sports
RCT	Randomized Control Trial
EF	External Focus of Attention
CCT	Continuous Cognitive Task
DL	Differential Learning
VMT	Visuo-Motor Training
COMB	Combination
KOOS	Knee Osteoarthritis Outcome Score
IKDC	International Knee Documentation Committee
TSK-CF	Tampa Scale of Kinesiophobia
COP	Center of Pressure
AP	Anterior-Posterior
ML	Mediolateral
MPF	Mean Power Frequency
SEBT	Star Excursion Balance Test
ECC	Eccentric
PLYO	Plyometric
CON	Concentric
SAP	Strengthening Agility Secondary Prevention

PERT	Perturbation
MCID	Minimum Clinically Important Difference

Chapter 1 Introduction

1.1 Background

Anterior Cruciate Ligament (ACL) tears are debilitating; and activity-related orthopaedic injuries that place a significant burden on both athletes and clinicians (Wohl et al., 2021;Onate et al., 2019). These injuries, among the most common and devastating for athletes, pose serious challenges in returning to preinjury performance levels and often lead to shortened athletic careers (Gokeler et al., 2022; Gokeler et al., 2019). Approximately 200,000 ACL injuries occur annually, with 75% of cases requiring surgical reconstruction within the first year (Machan and Krupps, 2021; Onate et al., 2019). Despite surgery and extensive rehabilitation, these injuries frequently lead to high rates of reinjury, including contralateral injury and secondary graft rupture (Grooms et al., 2023). Athletes returning to play after an ACL injury are at a 30- to 40-fold higher risk of reinjury compared to those with no prior ACL injury (Grooms et al., 2017). Young, active athletes, particularly those under 20 years of age, face heightened risks of reinjury in both the contralateral and ipsilateral knees (Beischer et al., 2020; Gokeler et al., 2022).

In addition to reinjury risks, patients undergoing ACL reconstruction (ACLR) frequently experience long-term pathological effects, including abnormal joint loading, knee osteoarthritis, meniscal tears, and osteochondral lesions (Gokeler et al., 2019; Wohl et al., 2021). Interestingly, Roper et al.,(2016) indicated that the choice of graft type minimally affected the prevalence of early arthritis, suggesting other contributing factors to these post-ACLR complications.

One promising approach for reducing reinjury risk is to extend the time between injury or reconstruction and the return to play (RTP) phase. However, a prolonged rehabilitation period can be challenging for both athletes and clinicians, especially given the insurance-imposed limits on post-surgical treatment sessions. This limitation can make it difficult to achieve full recovery when nine to twelve months of rehabilitation are typically required for safe RTP (Machan and Krupps, 2021). On

average, RTP takes approximately 11 months (Beischer et al., 2020). Although time allows for graft maturation, there may be additional reasons why a longer interval before RTP is beneficial (Gokeler et al., 2022). Machan and Krupps (2021) hypothesised that increased post-injury time allows athletes more opportunities to acquire diverse motor strategies. This finding raises the question of whether rehabilitation techniques can be optimised to accelerate motor learning and potentially reduce the RTP timeframes.

According to Haggerty et al. (2020), approximately 70% of ACL injuries occur due to non-contact mechanisms such as landing, pivoting, cutting, and rotational movements. These injuries are frequently linked to sensorimotor errors that result in impaired neuromuscular control. Such high-risk movement patterns are especially common in sports like soccer, basketball, netball, volleyball, and skiing, which place frequent and dynamic loads on the knee joint (Griffin et al., 2006; Hewett et al., 2010; Gokeler et al., 2022). Even after ACLR, lengthy rehabilitation, and RTP, many patients continue to exhibit altered motor control patterns, possibly due to neural inefficiencies (Roper et al., 2016). These altered patterns can impair motor performance and increase the risk of secondary injury upon returning to sports environments that demand greater cognitive processing and complex motor tasks than those in a controlled clinical setting (Wohl et al., 2021). Although initially protective, these neural compensations may contribute to an increased risk of secondary injuries and long-term complications post-RTP (Grooms et al., 2023).

In the context of ACL injuries, RTP is successful only when athletes return to their prior performance level with a minimised risk of new or recurrent injuries. Deciding when an athlete is ready for RTP is a complex and multifactorial process (Gokeler et al., 2022). Despite ongoing research aimed at optimising RTP testing to reduce secondary injury risks, there is significant debate regarding which tests best predict this risk. For instance, studies show little correlation between passing current RTP tests and avoiding secondary injuries, as these tests often fail to identify high-risk individuals (Machan and Krupps, 2021). Although current RTP test batteries can reduce ipsilateral graft rupture rates by up to 60%, they have been associated with a 235% increase in contralateral ACL injury risk (Gokeler et al., 2022). This may be due

to their inability to detect underlying neurocognitive or neuromuscular deficits, which can result in maladaptive movement patterns and poor motor control upon return to dynamic sporting environments. This risk level indicates a need for more comprehensive testing in RTP assessment, beyond standard testing measures, to ensure that athletes are fully prepared for the demands of competitive sport (Grooms et al., 2023).

The observed bilateral neuromuscular changes following unilateral injury suggest central nervous system (CNS) adaptations (Grooms et al., 2017). Grooms et al. (2023) propose that RTP testing should evaluate the degree of neurocognitive reliance during functional tasks, as this neural compensation often manifests as increased attentional focus on motor tasks that were previously automatic. While functional, this excessive cognitive demand may increase the risk of motor errors, compromising the overall safety during sports. This hypothesis is supported by evidence that increased cognitive load reduces the capacity for automatic motor control, making athletes more prone to motor errors when multitasking in unpredictable environments — a key contributor to non-contact ACL injuries (Grooms et al.,2023).

In recent years, ACL injuries have been increasingly understood as complex neurophysiological injuries rather than as purely musculoskeletal injuries. Surgical reconstruction primarily restores mechanical knee stability but cannot fully recover the neurosensory function of the ACL, which is rich in mechanoreceptors that relay essential sensory information to the CNS. Injury to these receptors disrupts dynamic joint position and movement feedback, triggering neuroplastic changes as a compensatory mechanism (Machan and Krupps, 2021).

Neuroplasticity, defined as the brain’s adaptive response to various stimuli, is evident after ACL injury and has been demonstrated through altered cortical activation patterns in individuals post-injury (Grooms et al., 2017). Because the brain is highly adaptive, the loss of sensory input post-ACLR drives this neuroplastic state, leading to compensatory changes in sensorimotor control that rely on heightened cognitive and visual processing (Wohl et al., 2021). This compensatory behaviour is theorised to reduce perceptual uncertainty to protect the injured joint, although it may ultimately create maladaptive movement patterns (Wohl et al., 2021). This neurophysiological

complexity is further amplified by the frequent involvement of the menisci and chondral surfaces in ACL injuries, as these structures also house mechanoreceptors critical for proprioceptive feedback. When damaged, they contribute to greater disruption of sensorimotor control and exacerbate neuroplastic compensations (Zimny & Wink, 1991).

Gokeler et al.(2019) highlighted that 95% of physical therapists prescribe exercises focused on visual attention to knee positioning, encouraging reliance on visual rather than proprioceptive cues, which may lead to suboptimal neuroplastic adaptations (Onate et al., 2019; Grooms et al., 2017). For athletes expected to perform in dynamic environments, this visual dependence can limit available neural resources for lower limb movement, posing an increased risk of reinjury (Wohl et al., 2021). Haggerty et al.,(2020) argue that traditional rehabilitation methods often fail to emphasize neuroplasticity or sensory reweighting, which are essential for optimizing neuromuscular function. This oversight restricts movement variability, pattern acquisition, and long-term motor retention (Machan and Krupps, 2021). Wohl et al. (2021) advocate using motor learning principles to develop resilient motor patterns that endure beyond clinical practice. These principles include, but are not limited to techniques such as differential learning (which promotes movement variability), implicit learning (which reduces reliance on conscious control), and external focus of attention (which directs attention toward the effects of the movement rather than the movement itself). According to Gokeler et al. (2019), neglecting sensorimotor integration within sport-specific contexts increases the risk of reinjury — a concern that extends beyond individual athletes to teams, especially in professional settings where player performance and availability are critical.

The likelihood of restoring mechanoreceptors in the ACL is low, which has led to the focus on leveraging neuroplasticity principles to regain neuromuscular function (Roper et al., 2016). As brain activation patterns change after injury, clinicians are encouraged to develop rehabilitation pathways that foster adaptive CNS responses (Onate et al., 2019). While strength training remains crucial, creating a rehabilitation environment that stimulates neuroplasticity across multiple brain areas is increasingly prioritised (Gokeler et al., 2022b). Motor learning principles, which are drawn from neuroscience, psychology, and orthopaedics, emphasise that ACL injuries often

result from coordination errors in sensory, visual, or motor processing, necessitating comprehensive neurophysiological rehabilitation (Haggerty et al., 2020).

This study aimed to determine whether leveraging neuroplasticity principles can shorten RTP timeframes and reduce risk of reinjury. “The opportunity to supplement traditional interventions by further targeting neuroplastic, cognitive, and visual-motor capabilities is an exciting time for research and clinical practice” (Onate et al., 2019, p. 415). Applying this emerging knowledge in rehabilitation presents a promising new approach in orthopaedic care with the potential to enhance patient outcomes, expedite recovery, and alleviate the impact of ACL injuries on athletic populations.

1.2 Problem Statement

Over the past decade, extensive research has been conducted on the neurophysiological mechanisms that predispose athletes to reinjury following ACLR, including altered sensorimotor control, cortical reorganization, and visual dependence for movement guidance (Grooms et al., 2017; Onate et al., 2019; Gokeler et al., 2019; Machan & Krupps, 2021; Haggerty et al., 2020).These findings suggest that traditional rehabilitation approaches may contribute to prolonged recovery times and increase the risk of reinjury. The extended rehabilitation period, time away from sports, and associated costs place a significant burden on athletes, often leading to early career termination.

Current rehabilitation and RTP protocols may not sufficiently address all physiological systems needed for optimal recovery outcomes. Traditional models prioritise pre-planned motor skills in controlled environments, potentially overlooking the attentional and environmental complexities emphasised by neuroplasticity-based approaches. This gap may explain why some athletes fail to fully regain motor skills post-injury, as current rehabilitation programs may inadequately stimulate neuroplasticity (Gokeler et al., 2019). A shift in rehabilitation strategy could bridge the divide between the intense neurocognitive and motor demands of sports and the more predictable, controlled settings of clinical recovery. This requires integrating

interventions that promote neurological adaptation alongside biomechanical techniques already in use (Onate et al., 2019).

Although significant research has aimed to refine the RTP process and mitigate reinjury risk after ACLR, little is known about safe methods to accelerate RTP. In my time in clinical practice, I have frequently heard of patients, particularly professional rugby players, who successfully complete a full rehabilitation programme, yet sustain a reinjury shortly after returning to sport. These recurring patterns raised the concern that current rehabilitation protocols may be overlooking critical components necessary for long-term success. Additionally, high-profile cases, such as Siya Kolisi's return to World Cup-level rugby at approximately 4.5 months post-ACLR—far earlier than the more typical 9-month timeframe—further fuelled my interest in understanding what factors may contribute to such accelerated recovery trajectories. These personal observations led to my interest in exploring whether neuroplasticity-based interventions may represent a missing link in optimising RTP readiness. Further investigation into this area could help reduce the substantial burden ACL injuries place on athletes' careers, health, and long-term participation in sport.

1.3 Aims and Objectives

The purpose of this review was to summarise and critically appraise the available literature on therapeutic interventions targeting motor learning and neuroplasticity, and to ultimately evaluate their effectiveness in accelerating RTP timelines and reducing reinjury rates following ACL reconstruction. Effectiveness was assessed using outcome measures commonly employed in RTP assessments post-ACLR, including functional performance tests, biomechanical measures, self-reported function, dynamic and static balance assessments, psychological readiness, and kinesiophobia scores. Specifically, the review aimed to:

- Compare the effectiveness of neuroplasticity and motor learning-based therapeutic interventions against traditional rehabilitation methods in athletes post-ACLR.
- Investigate the relationship between neuroplasticity, motor learning, RTP timelines, and reinjury rates in this population.

The review question was structured using the PICO (Population, Intervention, Comparison, Outcome) framework, resulting in the following query: “What is the effect of interventions targeting neuroplasticity on RTP timelines and reinjury risk in athletes following ACLR?”

The neuroplastic interventions examined in this review included various forms of motor learning, sensory reweighting, neuromuscular training, visuomotor training, exercises promoting movement variability, and neurocognitive exercises.

1.4 Significance

Extensive research has investigated predictors of reinjury following ACLR and the factors influencing safe RTP. While studies have shown that delaying RTP correlates with reduced reinjury risk, the mechanisms underlying this relationship remain uncertain (Gokeler et al., 2022). Machan and Krupps (2021) proposed that extended rehabilitation time may offer athletes the opportunity to adopt new or more refined motor strategies. This may result from increased repetition and exposure, regardless of the specific training modality. However, this review explores whether explicitly targeting neuroplastic mechanisms during rehabilitation — rather than relying solely on extended duration — may accelerate motor learning and improve RTP outcomes.

1.5 Outline of this Research Report

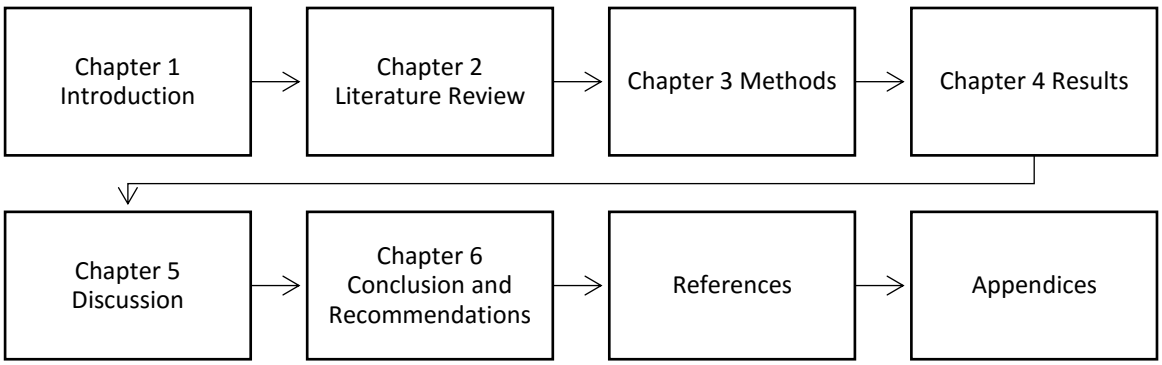

Figure 1. Outline of the research report

Chapter 2 Literature Review

2.1 Introduction

The literature review provides an in-depth exploration of the complex landscape surrounding anterior cruciate ligament (ACL) reconstruction. This background addresses the key issues by examining the burden, epidemiology, and risk factors associated with ACL injuries in athletes. The review then discusses the mechanisms of injury, potential long-term complications, and the critical role of rehabilitation in recovery and return to performance. A foundational overview of ACL anatomy, physiology, and function is presented to contextualize the importance of targeted rehabilitation.

A central focus of the review is neuroplasticity following ACL injuries, which provides an understanding of how neural adaptations can influence recovery. This section lays groundwork on how neuroplasticity-based rehabilitation strategies go beyond traditional methods. The limitation of conventional rehabilitation is highlighted, followed by a discussion on the shortcomings of the current return-to-play (RTP) guidelines. The literature review concludes by emphasizing the need for a paradigm shift within sports medicine, advocating for RTP protocols that integrate neuroplastic principles to enhance outcomes for athlete's post-anterior cruciate ligament reconstruction (ACLR).

2.2 Search Strategy

The search strategy focused on studies published between 2014-2024 to ensure relevant insights. A limited search of Google Scholar was undertaken to identify articles on the topic. The search engine was searched using the following keywords and index terms: ACL OR "anterior cruciate ligament" OR "anterior cruciate ligament injuries" OR "ACL injuries" OR "anterior cruciate ligament reconstruction" OR "ACL

reconstruction” OR “anterior cruciate ligament repair” OR “ACL repair” OR “anterior cruciate ligament surgery” OR “ACL surgery” OR “anterior cruciate ligament reconstruction” OR “ACL surgical reconstruction” AND “neuroplasticity” AND “rehabilitation” AND “return to sport”.

2.3 The Complex Landscape of ACL Injuries

2.3.1 The Burden, Epidemiology, and Risk of Anterior Cruciate Ligament Tears in Athletes

Anterior cruciate ligament tears are debilitating, activity-related orthopaedic injuries that pose a significant burden for both athletes and clinicians (Wohl et al., 2021; Onate et al., 2019). They rank among the most common and devastating injuries in sports, as they create substantial challenges for athletes striving to regain their preinjury performance levels and often lead to shortened careers (Gokeler et al., 2022(a); Gokeler et al., 2019). Machan and Krupps (2021) estimate that approximately 200,000 ACL injuries occur annually, with 75% of those injuries undergoing surgical reconstruction within the first year (Onate et al., 2019). Despite surgical intervention and extensive rehabilitation, these injuries are further complicated by high rates of reinjury, contralateral injuries, and secondary graft ruptures (Grooms et al., 2023). Athletes returning to play after an ACL injury face a 30 to 40 times greater risk of reinjury compared to those without a history of ACL issues (Grooms et al., 2017). Researchers have highlighted the increased risk of reinjury to both the contralateral and ipsilateral knees in active young athletes (under 20 years old) after returning to sports (Beischer et al., 2020; Gokeler et al., 2022(b)). Statistically, 25% of patients who return to high-level sports after ACLR will sustain a second ACL injury (Haggerty et al., 2020).

2.3.2 Mechanism of ACL Injuries

ACL injuries are primarily caused by non-contact mechanisms, typically involving movements such as landing, jumping, pivoting, and cutting (Haggerty et al., 2020; Gokeler et al., 2019). These high-risk movement patterns are particularly common in sports such as basketball, netball, soccer, volleyball, and handball, where athletes

frequently perform sudden decelerations, direction changes, and single-leg landings. The desire to return to the preinjury level of performance is the major reason for surgical reconstruction of this ligament, which aims to restore the mechanical stability of the joint as a prerequisite for RTP (Gokeler et al., 2019; Gokeler et al.,2022(b)). Since these non-contact manoeuvres demand various neuromuscular control strategies for proper execution, literature indicates that such injuries may stem from sensorimotor errors (Haggerty et al., 2020). Despite advancements in surgical techniques, persistent asymmetries in motor control among patients remain an underrecognized factor contributing to the high risk of both contralateral and ipsilateral secondary injuries (Grooms et al., 2023).

2.3.3 Long-Term Complications and Pathological Sequelae Following ACLR

In addition to the risk of reinjury, long-term pathological sequelae often develop following ACLR (Wohl et al., 2021). Common complications in patients after ACLR include aberrant joint loading, osteoarthritis of the knee, meniscal tears, and osteochondral lesions (Gokeler et al., 2019). Roper et al.,(2016) noted that the choice of graft type had minimal influence on the prevalence of early-onset arthritis, suggesting that other pathological factors may be involved.

These complications arise from various biomechanical, kinetic, kinematic, neuromuscular, and postural stability changes that occur as neural compensations following the injury (Gokeler et al., 2019). Kinetic and kinematic abnormalities can persist for up to seventeen months after surgery, even with successful completion of rehabilitation (Roper et al., 2016). During early RTP, patients typically face a rapid increase in motor task complexity and an overload of dynamic visual information due to the competitive environment. The combination of additional environmental stimuli and the psychological demands placed on patients can make it challenging to perform sensorimotor tasks without error, despite having practiced these movements extensively during rehabilitation sessions. These sensorimotor errors create opportunities for secondary injuries to occur, such as ipsilateral graft ruptures, contralateral ACL tears, meniscal damage, and early-onset osteoarthritis (Wohl et al., 2021; Gokeler et al., 2019).

2.3.4 The Role of Rehabilitation in Enhancing ACL Reconstruction Success

Postoperative rehabilitation plays an important role in successful recovery after ACL reconstruction. However, unless it effectively addresses lapses in sensorimotor control, it will join graft selection, patient compliance, and funding limitations as confounding variables affecting the success of ACLR. As our understanding of movement, tissue healing, and surgical techniques continues to advance, it is crucial that we also enhance our understanding of rehabilitation requirements. Studies indicate that only 81% of athletes return to sport after ACL injury, with just 65% achieving their preinjury performance levels and only 55% returning to competitive sport (Gokeler et al., 2019). Therefore, rehabilitation paradigms must be designed to better prevent the unwanted consequences of secondary injuries and pathological sequelae to improve these statistics as a reflection of successful ACLR (Machan and Krupps, 2021; Roper et al., 2016).

2.4 Anatomy, physiology and function of the ACL

The ACL is positioned in the centre of the knee joint and serves as a crucial mechanical stabilizer, limiting both rotation and anterior translation of the tibia on the femur. The individual fibres of the ACL are bundled together according to their orientation, allowing the ligament to provide stability at varying angles of knee flexion and extension. Specifically, the posterolateral bundle becomes taut toward the end ranges of extension, while the anteromedial bundle tightens during greater degrees of knee flexion (Prathap Kumar et al., 2020).

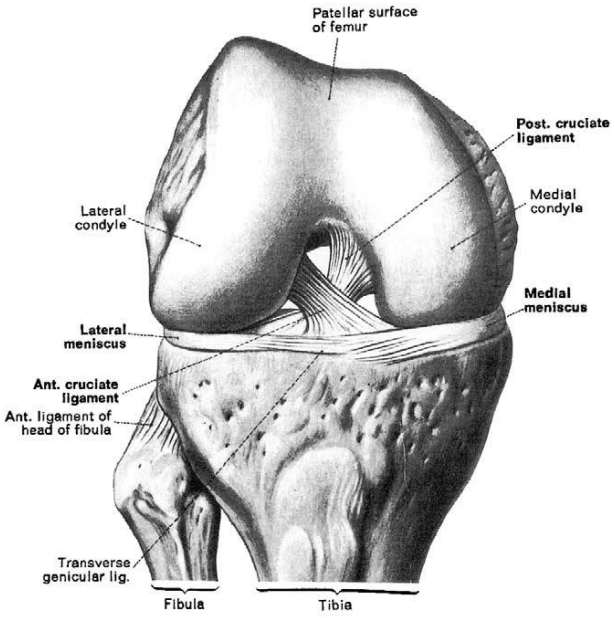

Figure 2 Image of the internal structures of the knee joint (Morimoto et al., 2021)

In addition to its stabilizing role, the ACL plays a significant part in proprioception (Onate et al., 2019). Unlike most ligamentous structures, it possesses robust afferent connections to the spinal cord and cerebrum. The synovial lining of the ligament is densely populated with mechanoreceptors, including free nerve endings, Ruffini end organs, Pacinian corpuscles, and Golgi receptors, which facilitate this connection with the central nervous system (CNS) (Onate et al., 2019). The afferent nerve fibres are primarily located near the femoral attachment of the ligament and feed into the articular branch of the posterior tibial nerve (Machan and Krupps, 2021). These mechanoreceptors are responsible for detecting deformation of the knee by sensing and transmitting critical information regarding joint position, motion, and acceleration (Wohl et al., 2021).

While the ACL is rich in mechanoreceptors, research indicates that similar structures exist in other soft tissues around the knee, such as the joint capsule, collateral ligaments, posterior cruciate ligament (PCL), and menisci. These structures may also contribute to knee stability (Seitz et al., 2021). Each type of mechanoreceptor has a unique role in maintaining functional stability:

- **Ruffini endings** respond to the movement of collagen fibres in the capsule or ligaments, regulating muscle tone.

- **Pacinian corpuscles** activate during the initiation or cessation of movement, sensing acceleration, quick movements, and vibrations, which lead to brief reflex changes in the muscle tone of surrounding muscles.
- **Golgi tendon organs** are associated with ligaments and menisci and become active with significant joint displacement, aiding in the modification of muscle tension, joint position, and movement direction.
- **Free nerve endings**, while not mechanoreceptors, detect pain, adding another layer of sensory feedback (Zimny & Wink, 1991).

2.5 Understanding Neuroplasticity following ACL Injuries: Mechanoreceptor Damage and CNS Adaptations

2.5.1 Deafferentation of the ACL following injury

Recent research has shifted understanding to view ACL injuries as complex neurophysiological injuries rather than merely musculoskeletal injuries (Gokeler et al., 2022(a)). While surgical reconstruction of the ACL aims to restore mechanical stability to the knee, it does not effectively restore the neurosensory function of the ligament. During both the injury and surgical reconstruction processes, damage to the mechanoreceptors results in a loss of critical information regarding joint position sense and movement. This loss triggers a neuroplastic response in the brain as a compensatory measure (Machan and Krupps, 2021). The physiological cascade following receptor damage alters the afferent input delivered to the CNS, particularly affecting the primary sensory cortex (Grooms et al., 2017). Consequently, a larger stimulus is required to activate the motor cortex for even simple quadriceps contractions. As a result, the frontal and parietal regions of the brain, which are highly connected to the motor cortex, increase their activity to provide sensory and cognitive support for motor planning. This compensatory mechanism is crucial for enhancing joint position sense and force control after injury.

2.5.2 Sensory reweighting as a mechanism of CNS Reorganization

After ACLR, the CNS undergoes reorganization, increasingly relying on alternative sensory inputs such as visual feedback, spatial awareness, and vestibular contributions, rather than proprioceptive processing. Numerous studies have demonstrated altered activation in brain regions responsible for sensory, motor, and visual-spatial processing (Grooms et al., 2017). This reorganization, referred to as sensory reweighting, manifests externally as proprioceptive deficits and impaired motor coordination. Together with heightened cognitive and attentional demands, this reweighting serves as a functional strategy to reduce perceptual uncertainty, thereby maintaining adequate motor control and postural stability to optimize performance (Wohl et al., 2021).

While these neural compensations can preserve certain functional elements, increased reliance on cognitive resources represents a less efficient neural activation strategy (Grooms et al., 2023). Neural efficiency is characterized by an expert's ability to perform learned skills with less neural activity than a novice, who often requires significantly more activation to achieve the same motor patterns. Novices or athletes recovering from ACLR depend on enhanced visual feedback or memory reliance, which drains CNS resources that would otherwise manage environmental interactions and maintain knee stability (Onate et al., 2019). This often results in heightened attention to movements that the athlete previously executed automatically (Grooms et al., 2023). Unfortunately, these deficits do not naturally resolve following reconstructive surgery; in fact, they can become more pronounced or even bilateral (Onate et al., 2019).

2.5.3 Motor control changes

Although patients may compensate for simple movements by increasing visual processing, an influx of dynamic visual information in a sporting environment can overwhelm neural processing resources. This overreliance on visual input heightens the risk of movement errors, ultimately increasing the likelihood of reinjury (Grooms et al., 2023). As motor control is the observable output of central processing and sensorimotor integration, such changes can disrupt movement accuracy, timing, and stability — all of which are critical during dynamic sport-specific tasks. Common changes in movement patterns associated with these compensatory mechanisms

include ipsilateral offloading strategies and deficits in postural stability, characterized by greater trunk-side flexion asymmetries, increased distance between the centre of mass and the knee and ankle in the frontal plane, pelvic tilting, and pelvic drop (Gokeler et al., 2022(b)). Despite the increased use of the contralateral leg due to ipsilateral offloading, the uninjured leg may weaken during the postoperative phase, likely due to changes within the CNS (Machan and Krupps, 2021).

2.5.4 The overarching theory of neuroplasticity following ACL injuries

For complete restoration of sensory input from the reconstructed ACL, it would be necessary to re-establish the free nerve endings and mechanoreceptors. Roper et al.,(2016) identified these receptors in reconstructed ACL's approximately ten years after surgery. However, Krogsgaard et al.(2011) argued that reinnervation of the reconstructed ligament is unlikely, leaving afferent information absent from the CNS. This discrepancy forms the basis for the overarching theory of neuroplasticity following ACL injuries. The disruption of somatosensory input from the reconstructed ligaments and the resulting CNS reorganization leads to motor control adaptations that compromise neuromuscular control of posture and gait, despite reconstruction and rehabilitation. Thus, while surgical reconstruction restores mechanical stability to the knee, it appears to exacerbate deafferentation, perpetuating neuroplastic changes (Onate et al., 2019).

2.6 Neuroplasticity and Rehabilitation following ACL Reconstruction

2.6.1 Defining neuroplasticity in the context of ACL injuries

"Neuroplasticity is a state of cortical adaptability and refers to the broad idea that the brain can adapt, and change based on internal and external stimuli" (Machan and Krupps, 2021, p. 4). The brain's plasticity means it can adjust according to the input it receives; thus, the loss of afferent input following ACLR is a primary factor driving the neuroplastic state observed in these patients (Machan and Krupps, 2021). The reinnervation of disrupted mechanoreceptors in the ACL is unlikely, prompting researchers to embrace neuroplasticity principles to restore neuromuscular function (Roper et al., 2016). Given that brain activation patterns can shift significantly after

injury, evidence suggests a need for clinicians to adopt innovative rehabilitation pathways that facilitate the brain's responsiveness to these changes through neuroplastic constructs (Onate et al., 2019).

Neuroplasticity is not inherently goal-oriented or directional, meaning changes in the CNS can be influenced by various factors, including behaviour, past experiences, injury-associated pain, instability, compensatory movement patterns, and rehabilitation methods (Machan and Krupps, 2021; Grooms et al., 2017). While strength training and other established musculoskeletal rehabilitation techniques remain essential, clinicians should focus on creating enriched rehabilitation environments that foster neuroplasticity across multiple brain regions (Gokeler et al., 2022(b)).

It is important to clearly differentiate between traditional rehabilitation methods and those specifically targeting neuroplastic adaptations. Traditional rehabilitation following ACLR primarily focuses on peripheral recovery, such as restoring muscle strength, joint stability, and biomechanical alignment, typically through structured, repetitive resistance exercises (e.g. squats, lunges, leg press) designed to induce hypertrophy and improve motor execution (Gokeler et al., 2019). While these protocols may indirectly influence the nervous system, they do not explicitly aim to engage central neuroplastic processes. In contrast, neuroplastic interventions are intentionally designed to influence central nervous system (CNS) reorganisation by incorporating sensory reweighting, cognitive engagement, and movement variability (Grooms et al., 2015; Onate et al., 2019; Machan & Krupps, 2021). For example, a traditional squat may emphasise correct execution under load, while a neuroplastic variation could introduce dual-tasking, external focus cues, or visual perturbations to challenge motor control and promote implicit learning. While some overlap can occur — such as a coach offering verbal cues during a traditional task — the key distinction lies in the intent and consistency of targeting CNS-driven adaptation as a core therapeutic goal.

2.6.2 Mismatch between clinical settings and the chaotic athletic environment

The neuroplastic changes resulting from ACL injury can create a misleading impression of adequate knee stability. This false sense of security arises from

compensatory neural processes, such as increased reliance on visual feedback, heightened activation of contralateral motor cortices, or reduced somatosensory input from the injured limb — all of which may mask underlying deficits and lead clinicians to prematurely conclude that a patient is ready for RTP (Grooms et al., 2023). However, the complex nature of athletic environments imposes demands on the CNS that differ significantly from those encountered in controlled rehabilitation settings. Rapidly changing circumstances in competitive scenarios often lead to cognitive loads that exceed neural processing capacity, causing athletes to narrow their focus on available sensory stimuli. This can result in inattention to visual input or motor control errors, thus increasing the risk of reinjury (Onate et al., 2019). To address this, clinicians should incorporate cognitive and perceptual challenge into rehabilitation — such as dual-task drills, unpredictable external cues, and sport-specific decision-making tasks — to better simulate competitive demands and prepare the CNS for real-world environments (Onate et al., 2019).

2.6.3 Visuo-motor & cognitive training

In dynamic sporting contexts, vision serves as the primary sensory input for decision-making regarding responses to changing external conditions. Following injury, cognitive processes that interpret visual input may not create an accurate internal representation of the external environment. This mismatch can lead to sensory-motor errors, impaired coordination, and increased reinjury risk. Visual-cognitive training has emerged as a valuable component of ACL rehabilitation, promoting desirable neuroplastic adaptations by engaging the visual system with environmental cues that closely mimic game-related scenarios. This training improves athletes' reaction times and processing speeds, enabling them to prepare for unexpected perturbations while maintaining neuromuscular control (Onate et al., 2019). Cognitive exercises may range from simple questions to more complex problem-solving tasks, such as counting backward and word association games (Onate et al., 2019; Machan and Krupps, 2021). These activities can be integrated into motor tasks to create distraction-based exercises that enhance patients' conscious attention while fostering the automaticity necessary for effective motor execution (Machan and Krupps, 2021).

2.6.4 Sensory Reweighting

Neuromuscular control encompasses a broad spectrum of human function, integrating sensory input, its processing, motor output generation, and overall coordination. The afferent system continuously updates the motor system regarding aspects of movement such as position, force generation, acceleration, and environmental representation (Onate et al., 2019). In a dynamic sporting environment, the brain utilizes various afferent inputs to update the motor system, with primary pathways arising from the vestibular, visual, and somatosensory systems. Depending on environmental demands, the brain weighs the contributions of each sensory system to ensure efficient and accurate motor output. After ACLR, the loss of proprioceptive input forces the brain to rely more heavily on vestibular and visual systems. This process, termed sensory reweighting, is a neuroplastic construct that, if properly understood and utilized by rehabilitation specialists, could facilitate positive neuroplastic adaptations (Onate et al., 2019; Gokeler et al., 2019).

The objective of sensory reweighting in the context of ACL injuries is to redistribute the CNS's reliance on visual inputs back onto the remaining proprioceptive inputs arriving from the knee. The intact mechanoreceptors found in other structures within and around the knee, such as the joint capsule, menisci, ligaments, and muscle spindles, can be upregulated to compensate for the absent afferents from the injured ACL. In rehabilitation, this can be achieved by incorporating exercises that induce visual perturbation. By creating environments with disrupted or constantly changing visual input during motor tasks, reliance on visual cues can be diminished. Techniques such as pinhole and stroboscopic glasses, blindfolds, or moving targets can be employed during agility drills, balance tasks, plyometrics, running, cutting, and pivoting (Haggerty et al., 2020). Although visual input is the most easily manipulated, any sensory modality can be adjusted to elicit neuroplastic adaptations. “If rehabilitation specialists acknowledge neurophysiological dysfunction and implement known parameters to effect positive neuroplastic changes, the logic follows that outcomes will improve” (Machan and Krupps, 2021, p. 4).

2.6.5 Vestibular-ocular reflex training

In addition to manipulating visual input, vestibular-ocular reflex exercises can be utilized to challenge the vestibular system. While oculomotor exercises train specific visual skills in isolation, head movements during competition can distort the visual images processed by the CNS, making vestibular training a crucial complement to visual training. Rehabilitation environments can be tailored to induce vestibular disturbances by transitioning from simple to busy settings and varying target movements from stationary to unpredictable positions. Targets can include rehabilitation equipment, computer programs, colourful cue cards, or hand gestures (Onate et al., 2019).

2.6.6 Dual-tasking

Rehabilitation can be customized to match the specific demands of a player's sport and position on the team, by employing diverse sensory manipulation techniques. For instance, some athletes may require advanced ball-handling skills, while others may need enhanced hand-eye coordination (Onate et al., 2019). By selectively challenging sensory systems, clinicians can reduce dependence on those systems to achieve correct motor execution (Machan and Krupps, 2021). This approach, known as dual tasking, involves executing two or more tasks simultaneously to target neurocognitive function (Wohl et al., 2021). A clinician selects a primary task, then based on the patient's requirements, adds a secondary or tertiary task to diminish the attentional resources available for completing the primary task, fostering greater interaction with the environment (Machan and Krupps, 2021). This is an essential component for preventing reinjury, because dual-task training simulates the cognitive and motor demands of competitive sport, helping athletes regain automaticity and adaptability under pressure (Wohl et al., 2021).

2.6.7 Motor learning principles

To optimize the neuroplastic state of the CNS, considerations of motor control and motor learning principles are essential. Motor learning can be described as "the process of acquiring or altering motor skills to create a permanent change in performance" (Machan and Krupps, 2021, p. 3). The principles of motor learning

encompass aspects of neuroscience, psychology, and orthopaedic rehabilitation to explain how motor development and relearning occur post-injury. Non-contact ACL injuries often stem from coordination errors in sensory, visual, or motor processing, necessitating rehabilitation strategies that address these factors (Haggerty et al., 2020). While strength training is crucial following ACLR, it does not adequately address the motor learning required after a neurophysiologic injury (Machan and Krupps, 2021). “Given the reorganization of the CNS following an ACL injury, we must identify which motor learning principles could enhance neuroplastic processes that translate into effective motor learning interventions for optimal patient function” (Gokeler et al., 2019, p. 182).

Differential learning is a motor learning principle that involves practicing varied movement patterns with minimal repetition and no corrective feedback, allowing the athlete to explore a wide range of motor solutions and self-organize the most efficient strategies (Schöllhorn et al., 2012). One such principle promotes functional variability in the movement system and is expected to play a role in preventing reinjury. It encourages patients to actively explore multiple movement solutions, facilitating the discovery of individual movement patterns that enhance performance adaptability and fluidity. Integrating differential learning into ACL rehabilitation allows patients to identify and choose more appropriate motor solutions in response to task and environmental constraints, rather than striving for a universal standard for motor patterns. This flexibility fosters adaptability to changing environments and enables skilled responses to situational variations. Literature suggests that rehabilitation should intentionally manipulate environmental constraints to maximize movement variability and exploration, rather than adhering to prescriptive instructions, to reduce reinjury risk (Mohammadi Orangi et al., 2021). Practically, this could involve designing an exercise program that incorporates frequent changes in technique, environment, duration, and intensity. Unlike traditional exercise prescription methods, differential learning mandates task modification every few repetitions to promote variation and encourage adaptation to dynamic conditions (Haggerty et al., 2020).

In addition to altered activation patterns in cortical regions, studies have shown decreased activation in the cerebellum following ACL injuries. This suggests a loss of

movement automaticity and an increased need for attentional awareness (Machan and Krupps, 2021). Implicit learning, a principle of motor learning, seeks to reduce reliance on conscious memory to promote more automatic processes (Gokeler et al., 2019). Automatic movements are more neurally efficient, enabling athletes to allocate conscious resources to other performance aspects. Implicit learning employs an external focus of attention during movement, directing a patient's conscious thought away from their body toward the effects of their movements on the environment. In contrast, an internal focus of attention, which relies on conscious control, can disrupt automatic processes and necessitate the patient's return to memory for movement execution. "Such evidence may explain why patients do not always regain motor skills after ACL injury, as the neuroplastic capacities may not be optimally challenged in current rehabilitation practices" (Gokeler et al., 2019, p. 183). Clinicians can facilitate an external focus by using instructional cues that resemble analogies rather than direct commands. Metaphorical descriptions of movements help patients visualize actions, enhancing their ability to perceive movement changes as they occur. This seemingly minor adjustment in cueing can significantly influence CNS movement generation and result in improved motor learning outcomes (Gokeler et al., 2019).

Another beneficial motor learning principle for patients following ACLR is self-controlled learning. Allowing patients to select exercises from a list promotes enjoyment, interest, and motivation throughout their rehabilitation sessions. Motivation positively impacts motor learning, while positive reinforcement and encouragement from clinicians during successful task execution enhance competence, compliance, and motor learning optimization (Gokeler et al., 2019). However, despite selecting enjoyable exercises, many patients continue to experience a persistent fear of reinjury, which may limit their willingness to fully engage in physical tasks and inhibit motor learning (Gokeler et al., 2019). Clinicians must therefore balance autonomy and enjoyment with graded exposure to sport-specific challenges, while actively addressing fear-based movement avoidance through reassurance and confidence-building strategies.

2.6.8 Virtual Reality

Advancements in technology continue to introduce innovative modalities aimed at maximizing neuroplasticity during rest periods or downtime in athletes' schedules. For instance, virtual reality is being employed to immerse patients in simulated fields of play, exposing them to various perturbations as they observe dynamic environments. As rehabilitation progresses, virtual reality applications can be enhanced to promote training of postural control (Haggerty et al., 2020). Machan and Krupps (2021) recommend incorporating various sensory stimuli and problem-solving tasks as early as possible after ACLR to maximize neuroplastic potential. "The capacity for neuroplasticity after injury and during therapy presents an opportunity to bridge the gap between rehabilitation and activity by targeting a broader spectrum of sensorimotor function during neuromuscular training" (Onate et al., 2019).

2.7 The Failures of Conventional ACL Rehabilitation and the Need for a Neuroplasticity-Focused Approach

2.7.1 Impact of Visually-Dominated Rehabilitation on Sensorimotor Adaptation and Reinjury Risk

Gokeler et al.,(2019) found that 95% of physical therapists prescribe exercises focusing visual attention on the knee, thereby increasing cognitive resources allocated to knee position control. These visually dominated exercises fail to encourage reliance on sensorimotor and proprioceptive signals, leading to suboptimal neuroplastic adaptations (Onate et al., 2019; Grooms et al., 2017). The brain activation differences observed in patients following ACLR may, in part, result from this rehabilitation approach (Grooms et al., 2017). Utilizing vision to guide motor control can be maladaptive for athletes who must return to chaotic sporting environments. The new demand to integrate dynamic visual information may limit the neural resources the CNS can deploy for lower limb movement (Wohl et al., 2021).

Although visually dominated exercises remain prevalent, some protocols do incorporate visual deprivation techniques—such as eyes-closed balance tasks or stroboscopic glasses—as part of a proprioceptive or cognitive progression. These approaches aim to reduce visual dependency and enhance somatosensory integration, but they are not yet widely adopted or standardised across rehabilitation settings (Grooms et al., 2015).

Exercises prescribed during the early stages of rehabilitation often emphasize increased quadriceps activation. While this can positively impact motor patterns and muscle contractions, a prolonged internal focus on the knee can foster a maladaptive visual-motor link throughout the recovery process (Onate et al., 2019). Haggerty et al.,(2020) argue that traditional rehabilitation models do not prioritize neuroplasticity or sensory reweighting to optimize neuromuscular function. Consequently, these models fail to adequately address movement variability, movement pattern acquisition, and long-term retention of motor patterns, leaving aberrant movement patterns and risky biomechanics unchanged (Machan and Krupps, 2021; Gokeler et al., 2019). Wohl et al. (2021) suggest incorporating motor learning principles to facilitate the acquisition of injury-resistant motor patterns that extend beyond clinical settings. Gokeler et al.,(2019) emphasize that neglecting the interaction between sensory cues and motor responses in the context of specific sports activities, along with task and environmental constraints, increases the risk of reinjury. By integrating motor learning principles aimed at modifying sensorimotor neural processing, we may target injury-induced neuroplastic changes that standard therapy has yet to address effectively.

2.7.2 Bridging the Gap: The Need for Neuroplastic Rehabilitation in ACL Recovery

In addition to the risk of second ACL injuries, the early onset of osteoarthritis in patients following ACLR highlights the urgent need for improved rehabilitation methods. Despite ample evidence showing persistent faulty biomechanics or altered movement strategies post-rehabilitation, orthopaedic medicine has only recently begun to explore how injuries influence the CNS. Traditional rehabilitation approaches often focus solely on biomechanical factors such as range of motion, muscle strength, balance, and plyometric function, which may revert to pre-intervention levels or fail to induce improvement altogether (Onate et al., 2019). Current methods that emphasize pre-planned motor skills in predictable environments overlook the attentional and environmental components strongly encouraged by neuroplastic approaches (Gokeler et al., 2019).

It is important to acknowledge that certain contemporary frameworks, such as the Control-Chaos Continuum, have begun to incorporate progressive cognitive, perceptual, and neuromuscular demands into return-to-play protocols. These

approaches recognise the need to transition athletes from controlled environments to chaotic, unpredictable sport-specific scenarios, and share many principles with neuroplastic rehabilitation — including movement variability, decision-making under pressure, and dual-task integration (Gabbett et al., 2016). While not always explicitly labelled as neuroplastic, such frameworks represent important strides in aligning RTP strategies with the realities of competitive sport.

Athletes in team sports frequently operate in rapidly changing and unpredictable environments, presenting unique challenges that rehabilitation laboratories struggle to replicate accurately. The fundamental distinction between rehabilitation settings and competitive playing fields lies in the interactions between patients and their environments (Gokeler et al., 2022(a)). The way exercises are prescribed in rehabilitation settings is not conducive to mimicking real-life competitive play. In competition, opportunities to perform repetitive 'ideal' movements are rare. Rapid and variable movement performance cannot be trained through continuous repetition with the "correct" form for a predefined number of sets, which is characteristic of current standard rehabilitation practices (Haggerty et al., 2020; Gokeler et al., 2019).

To bridge the gap between the intense neurocognitive and motor control demands of sports and the clinical setting, ACLR rehabilitation must evolve. This evolution necessitates tailoring treatment to create positive neuroplastic changes through interventions that target neurological factors in addition to the biomechanical techniques currently emphasized (Onate et al., 2019).

2.8 Traditional RTP Guidelines: Navigating Challenges and Evolving Perspectives

2.8.1 Need for More Comprehensive RTP Testing Beyond Traditional Criteria

RTP after an ACL injury can only be deemed successful when the athlete is able to return to their previous performance level while maintaining a reduced or acceptable risk of new or recurrent injuries (Gokeler et al., 2022(b)). However, determining the appropriate timing for an athlete's RTP is a complex and multifaceted decision

(Gokeler et al., 2022(a)). Despite ongoing efforts by researchers to establish an effective battery of RTP tests aimed at minimizing the risk of secondary injuries, controversy persists regarding which assessments most accurately predict this risk. Notably, there appears to be no correlation between passing current RTP tests and the incidence of secondary injuries, as these assessments often fail to identify patients who eventually suffer such injuries (Machan and Krupps, 2021).
Authors focused on RTP are actively seeking objective measures that provide greater accuracy, enabling clinicians to make informed decisions. However, these decisions are inherently context-dependent, varying across different sports, player positions, and individual characteristics, underscoring the ineffectiveness of a “one size fits all” approach (Gokeler et al., 2022(a)). The current RTP test batteries include a range of assessments, such as strength testing, limb symmetry indices (LSI), hop tests, movement quality assessments, biomechanics evaluations, psychological readiness tests, and patient-reported outcomes. A systematic review revealed that 65% of patients were reluctant to RTP due to a fear of reinjury, highlighting the need for integrating psychological and cognitive evaluations alongside physical assessments to adopt a more holistic approach during the RTP process (Gokeler et al., 2022(b)).

While Gokeler et al.,(2022)(b) found that current RTP tests could reduce graft ruptures by up to 60%, they simultaneously observed a staggering 235% increase in the risk of contralateral ACL injuries. This significant risk warrants further investigation into the factors contributing to these outcomes that are overlooked in traditional RTP testing. The minimum requirement for RTP includes the complete recovery of isolated musculoskeletal impairments and, specifically for ACL injuries, the restoration of knee stability. However, these criteria do not guarantee that the athlete is prepared across all physiological domains affected by injury and competition demands.

2.8.2 Evaluating RTP Readiness through Dual-Task Neurocognitive Testing

Grooms et al.,(2023) propose a more accurate method for assessing RTP readiness by designing tests that evaluate the degree of neurocognitive reliance through dual-

tasking conditions integrated into established functional performance tests. Although the recovery of isolated musculoskeletal impairments is essential for RTP, incorporating dual-tasking scenarios would allow clinicians to assess neurocognitive functions such as reaction time, working memory, gaze control, and visual-spatial attention. For instance, tests could involve distracting proprioception while requiring the athlete to make task-relevant decisions, thus engaging their compensatory visual cognition and promoting implicit, proprioceptive control of movement. This approach could effectively reveal the extent to which the patient relies on neurocognitive strategies to mask underlying neural compensation.

Additionally, performance tests that incorporate sport-specific complexities—such as linear speed (measured by 10m sprint times) and change of direction (assessed via 5-0-5 agility and Agility T tests)—can be executed under dual-task conditions to provide further insight into RTP readiness. Methods such as simple light-timing systems, PowerPoint slides, flashcards, auditory cues, and hand signals can introduce reactive challenges to cognition during these performance assessments (Grooms et al., 2023).

2.8.3 Does Delayed RTP Significantly Reduce the Risk of ACL Reinjury?

Research indicates that athletes returning to knee-strenuous sports within nine months post-ACLR face a seven-fold increased risk of sustaining a second ACL injury (Beischer et al., 2020). Furthermore, Machan and Krupps (2021) discovered that delaying RTP from six to nine months can reduce the risk of reinjury by more than 50% for each month of postponement. Thus, the time elapsed between ACLR and RTP emerges as a crucial consideration in the RTP process. Various studies have discussed potential explanations for this phenomenon. One hypothesis posits that extended recovery time allows for increased strength development and improved psychological readiness (Machan and Krupps, 2021). Another suggests that additional time facilitates further graft maturation (Gokeler et al., 2022(a)). The most compelling hypothesis indicates that prolonged recovery allows for the acquisition of more motor strategies and experiences, ultimately contributing to enhanced movement variability. Machan and Krupps (2021) aptly question, “If time is truly just allowing the patient to

learn more movement strategies and increase their variability, is there some way to accelerate that process?”

2.9 Conclusion

This literature review explored the multifaceted challenges and advancements in anterior cruciate ligament (ACL) reconstruction and rehabilitation, emphasizing the integration of neuroplasticity-based approaches. The burden, epidemiology, and mechanisms of ACL injuries, alongside the limitations of traditional rehabilitation methods and return-to-play (RTP) guidelines is discussed. The review highlights how neuroplastic adaptations, triggered by ACL injuries, can influence motor control and proprioception, necessitating innovative rehabilitation strategies. Advocating for dynamic, environment-specific interventions such as sensory reweighting, dual-tasking, and virtual reality training, calls for a paradigm shift in sports medicine. The ultimate goal is to enhance recovery outcomes, reduce reinjury rates, and support athletes in achieving optimal performance post-ACL reconstruction.

Chapter 3 Methods

3.1 Study Design

This study was a Systematic Review of Effectiveness. It was conducted in accordance with the Joanna Briggs Institute (JBI) methodology for systematic reviews of effectiveness (Aromataris & Munn, 2020) and followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021). This protocol was registered in PROSPERO (CRD42024558847).

3.2 Eligibility criteria

3.2.1 Participants

This review examined studies involving athletes of any age, gender, and ethnicity participating in both contact and non-contact sports who had undergone an anterior cruciate ligament reconstruction (ACLR). The review focused specifically on athletes who sustained an anterior cruciate ligament (ACL) injury from a non-contact mechanism, excluding those with secondary or additional knee injuries at the time of the initial injury. Research has shown that similar neuroreceptors are present in multiple capsuloligamentous structures within the knee joint, allowing for compensation and upregulation of remaining receptors after knee injury (Seitz et al., 2021). This mechanism helps ensure that afferent sensory information is still transmitted to the central nervous system (CNS) after injury, thereby aiding proprioception.

While this review focused specifically on isolated ACL injuries to more accurately assess the neuroplastic effects of ACL damage and rehabilitation, it is acknowledged that this approach limits the generalizability of findings. Evidence suggests that up to 65% of ACL injuries occur alongside meniscal or chondral lesions (Sanders et al., 2016), meaning that isolated ACL injuries comprise a smaller, though clinically

significant, subgroup. As such, this focused approach improves internal validity but may reduce external applicability — a limitation discussed in the final chapter.

The term “athletes” encompasses a broad range of individuals. To help clarify this term, this review followed the guidelines proposed by Williams et al.,(2017), to evaluate the term’s suitability within the context of the study. Williams et al.,(2017) recommended that, in the absence of specific performance data, competitive experience and success in highly competitive leagues should be emphasized over international representation when defining “athletes” in team sports. While this review provided as much detail as possible regarding the competitive level of all participants, the final interpretation of “athlete” was left to the reader. Studies that included mixed populations, such as elite and non-elite athletes, were included if “athlete” was explicitly used as a descriptor for the participants.

3.2.2 Interventions

This review included studies that evaluated neuroplasticity-targeted interventions for ACLR rehabilitation across any sport. These multifaceted programs encompassed various components, including (but not limited to) motor learning, neuromuscular training, visuo-motor training, exercises aimed at movement variability, and neurocognitive exercises. All eligible studies were considered regardless of how the program was administered. Interventions delivered by physiotherapists, sports trainers, sports scientists, researchers, and research assistants were also included. The effectiveness of these interventions was assessed using the outcome measurement tools specified in the outcomes section below.

The review did not exclude studies based on the athlete’s participation level, and interventions were accepted regardless of whether they were applied to recreational, amateur, or elite athletes. However, it is acknowledged that participation level may influence intervention delivery, intensity, and access to resources such as neurocognitive training tools or sport-specific rehabilitation environments.

3.2.3 Comparator

This review considered studies that compared neuroplasticity-focused interventions (as described in the previous section) to traditional rehabilitation protocols typically provided after ACLR. When standard rehabilitation included elements like those in the intervention, these elements were treated as part of the standard approach. Only unique components of the intervention were evaluated for their effectiveness in reducing RTP timeframes and preventing reinjury. Studies without a clearly defined comparator group were excluded from the review.

3.2.4 Outcomes

This review considered studies that included the following outcome measures:

- Static and dynamic balance (e.g. Single-Leg Balance Test, Y-Balance Test)
- Functional performance tests (e.g. Single-leg hop for distance, Triple hop test)
- Biomechanics and sports performance tests (e.g. 3D motion analysis during jump-landing, Cutting maneuvers)
- Knee joint position sense (e.g. Joint angle reproduction test, Threshold to detect passive motion)
- Vertical ground reaction force (e.g. Force plate analysis during landing or squatting tasks)
- Psychological kinesiophobia status (e.g. Tampa Scale for Kinesiophobia, ACL-RSI scale)
- Functional knee assessments (e.g. Lachman test, Pivot shift test)
- Patient-reported function (e.g. IKDC subjective form, KOOS)
- Isokinetic muscle strength performance (e.g. Peak torque of quadriceps and hamstrings at 60°/s and 180°/s)

While all included outcome measures were relevant to post-ACLR recovery, it is acknowledged that many primarily assessed physical or functional performance (e.g., hop tests, balance scores, self-reported function). These tools are widely used in clinical decision-making and reflect traditional rehabilitation goals, but may not directly capture the central nervous system adaptations targeted by neuroplasticity-focused interventions. Currently, there are very few validated outcome measures designed specifically to assess neuroplastic changes in the context of musculoskeletal rehabilitation (Grooms et al., 2015). As such, there is a clear need

for future research to develop and validate assessment tools that can more accurately evaluate sensorimotor integration, cortical reorganisation, and motor learning. Nonetheless, it is hoped that positive neuroplastic changes would ultimately manifest in improved performance on conventional functional tests, given their dependence on effective motor control and sensorimotor coordination. Through inference, interpretation, and application, these outcome measures informed the RTP timeframe as the primary outcome of interest and the risk of reinjury after successful RTP as the secondary outcome of interest.

The included studies reported a wide range of outcome measures, including functional performance tests (e.g., hop tests, balance tasks), psychological readiness scales (e.g., ACL-RSI, TSK), and biomechanical assessments. While these individual outcomes varied, they were interpreted in relation to either return-to-play readiness or reinjury-related risk factors. RTP timeframe was determined when studies explicitly reported time to RTP, or inferred from criteria-based clearance markers (e.g., achieving specific test scores or benchmarks). Risk of reinjury was included as a secondary outcome when studies either reported reinjury incidence or evaluated proxies associated with increased reinjury risk — such as biomechanical asymmetries, persistent movement deficits, or elevated fear of reinjury. These inferences were based on established literature linking such factors to RTP decision-making and reinjury likelihood (Ardern et al., 2014; Gokeler et al., 2019).

3.2.5 Types of Studies

This review included randomized controlled trials and analytical cross-sectional studies. Studies containing predefined keywords in their entirety or at least in the title, keywords, or abstract sections were included. Conversely, papers that were duplicated within the search documents, inaccessible papers, review articles, meta-analyses, and studies that were not classified as primary research were excluded from the review.

Randomised controlled trials (RCTs) were prioritised for their methodological strength in assessing intervention effectiveness. Analytical cross-sectional studies were also eligible for inclusion if they compared participants exposed to a neuroplastic-focused intervention with a control or standard care group, and met all other inclusion criteria.

Although pre- and quasi-experimental designs were not excluded during the initial screening phase, none met the full eligibility criteria for methodological quality, outcome relevance, or population specificity. Therefore, only RCTs and analytical cross-sectional studies were ultimately included in the final synthesis.

3.3 Search Strategy

The search strategy aimed to locate both published and unpublished studies. Initially, a limited search of MEDLINE (PubMed) was undertaken to identify articles on the topic. The text words contained in the titles and abstracts of relevant articles, along with the identified keywords and index terms used to describe these articles, were utilized to develop a comprehensive search string.

A three-step search strategy was created with the assistance of an expert research librarian from Wits University. First, a preliminary test of the search string was conducted using MEDLINE (PubMed). The search strategy was piloted to refine it by removing duplicate or inadequate search terms, followed by retesting as necessary to ensure it was sufficiently sensitive to identify all relevant studies.

Secondly, the search strategy, encompassing all identified keywords and index terms, was adapted for each bibliographic database. Keywords were searched in titles and abstracts, index terms, and, where applicable, MeSH terms.

Thirdly, a search was performed on the reference lists of studies selected for critical appraisal to identify additional studies for inclusion in the review. Theses and dissertations found in grey literature databases were also included. Furthermore, known experts were contacted to identify any additional publications.

The following databases were searched with the help of a librarian: Scopus; MEDLINE (PubMed); SPORTDiscus (EBSCO); PEDro; CINAHL Complete (EBSCO); ClinicalKey; ScienceDirect (Elsevier); Health and Medical Complete (ProQuest); Cochrane Central Register of Controlled Trials (CENTRAL); and any other databases recommended by the Wits Health Sciences library. Sources of unpublished studies and grey literature searched included ProQuest Dissertations and Theses Global.

Studies published by authors of specific papers were contacted three times to provide missing details and clarifications. Any disagreements that arose between reviewers were resolved through discussion or with the assistance of a third reviewer. All papers underwent data extraction irrespective of quality, and the appraisal results were displayed in a summary table.

An initial search on PubMed highlighted that neuroplasticity's role in sports injuries is a developing area of research. Limiting the timeframe to studies published from January 2013 onward allowed for the inclusion of research that more directly addressed neuroplasticity concepts in rehabilitation. Although motor learning theory itself is not time-bound, more recent literature increasingly incorporates principles such as neuroplasticity, dual-task training, and sport-specific cognitive challenges — aligning more closely with the aims of this review. The decision to use 2013 as a cut-off was intended to reflect this evolution in application, though it is acknowledged that some foundational studies may have been excluded; this is noted as a limitation. Only studies published in English were included due to resource constraints related to translation and to maintain consistent interpretation of theoretical terminology across all reviewed texts.

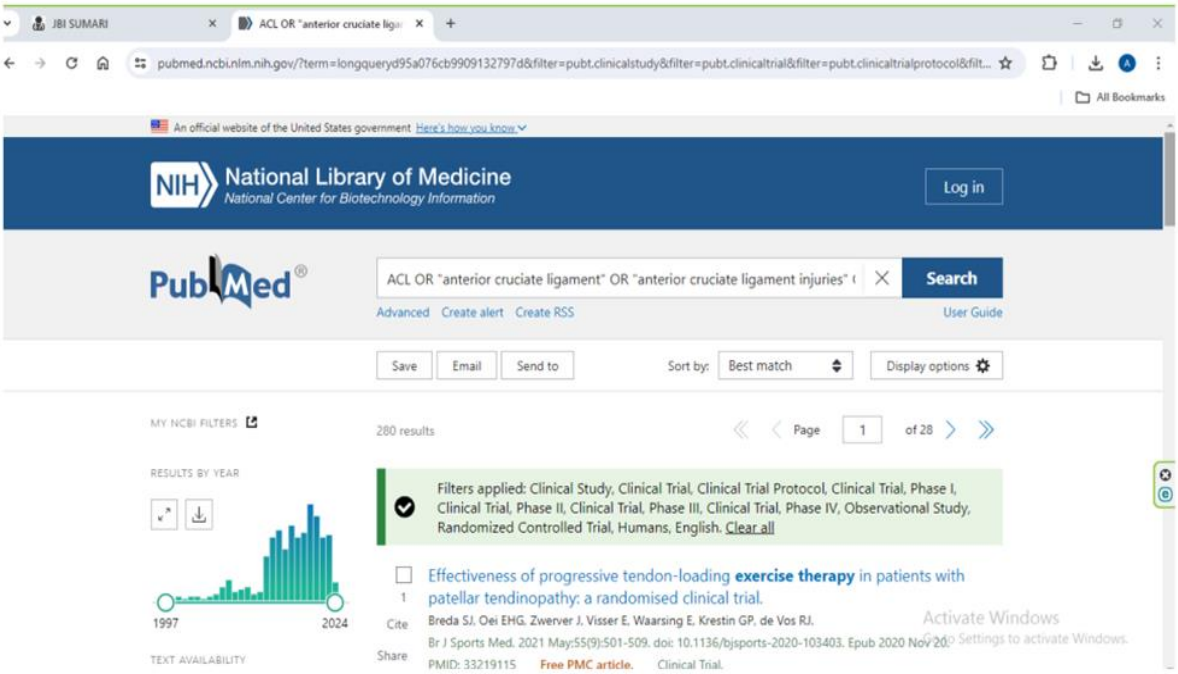

Figure 3 A screen shot to show the increase in ACL-related publications in recent years

3.4 Selection of Studies

All identified citations retrieved from the database search were collated and imported into Mendeley Reference Manager, where all duplicates were removed. The citations were then imported into the JBI System for the Unified Management, Assessment, and Review of Information (JBI SUMARI)(Munn et al., 2019). Following a pilot test in which two reviewers screened at least three studies, all abstracts and titles were screened in JBI SUMARI (Joanna Briggs Institute, University of Adelaide, Australia) by the two independent reviewers to assess their alignment with the inclusion criteria for this review. Studies with unclear titles and abstracts were also included for further screening.

The author, conducted the full-text assessment of eligible studies, and a second independent reviewer independently reviewed all full-text articles to ensure consistency with the inclusion criteria. Full-text articles that did not meet the inclusion criteria were excluded from the study, and the reasons for exclusion were recorded

and reported in the final systematic review. No disagreements arose at any stage of the review process; therefore, the involvement of a third reviewer was not required. The search results and the study inclusion process were fully reported in the final systematic review and presented in a PRISMA flow diagram (See Figure 2).

3.5 Critical Appraisal

High-quality evidence is essential for clinical practice protocols and guidelines, and evidence used in systematic reviews must undergo critical appraisal to assess quality, rigor and potential biases.

Critical appraisal was conducted independently by the author and the second independent reviewer using the appropriate checklists available within the JBI SUMARI platform (Joanna Briggs Institute, University of Adelaide, Australia). Any discrepancies in scoring were discussed and resolved by consensus. As no significant disagreements arose, the involvement of a third reviewer was not required. The JBI critical appraisal tool for randomised controlled trials ((Barker et al.,2023) was used for RCTs, and the tool for analytical cross-sectional studies (Moola et al.,2020) was used for the relevant observational studies. No other appraisal tools were necessary, as no additional study designs met the eligibility criteria for inclusion.

Although some studies had minor details missing, sufficient information was available to allow for appraisal without the need to contact any authors. Any reasons for exclusion at the full-text stage were documented in the final review, and a table accompanied by a supporting narrative illustrated the results of all critical appraisals performed.

For a study to receive a positive response to a critical appraisal question, it needed to provide sufficient detail for a reviewer to answer all dimensions of the question without doubt. Conversely, to receive a negative response, the authors had to supply enough information to allow the reviewer to formulate an explanation that

contradicted the specific question’s requirements. If a study received an 'unclear' response, it was because the reviewer could not confidently answer the appraisal item due to insufficient, ambiguous, or missing information in the published report. All studies, regardless of their methodological quality, underwent data extraction and synthesis. The quality, reliability, and relevance of each study were considered while formulating the review conclusions. The methodological quality of each study contributed to the "weighting" of influence its results could hold in comparison to others. Reasons for exclusion at the full-text review stage were listed in a table in the appendices, and the number of exclusions is reflected in the PRISMA flow diagram.

3.6 Data Extraction

Data from the included studies were extracted independently by the author and a second independent reviewer using the standardized JBI SUMARI data extraction tool (Munn et al., 2019) wherever applicable. All data were extracted manually without the use of automation tools. The extracted data were relevant to the study objectives and were presented in several tables. These tables included, but were not limited to, the following details: authors' names, article names, article titles, year of publication, country of study, setting and context, methodology, research design, variables, and results. Special attention was given to the following variables in each study:

- Participants: number of participants, type and level of sport played, age, gender, ethnicity, mechanism of initial injury
- Neuroplastic interventions: intervention type, content, dosage, frequency, the phase of rehabilitation during which they were introduced, and the provider responsible for delivering the intervention.
- Traditional rehabilitation methods: intervention type, content, dosage and frequency, and who delivered the intervention
- Compliance and follow-up
- Outcomes: as listed under the outcomes section
- Critical appraisal rating

A pilot data extraction was conducted to familiarize the two independent reviewers with the tool and to evaluate its appropriateness for this study. This pilot run also helped minimize data extraction errors in the main study. Once the two reviewers were comfortable with the process, they independently extracted the relevant data. If a dispute arose between the reviewers, a third reviewer was involved to resolve the disagreement. Confounding factors reported in the included studies were also extracted and accounted for. Where necessary, missing or additional data were requested from the authors of the papers. In cases where no response was received from an author, a reminder email was sent ten days after the initial email.

3.7 Data Synthesis

Due to substantial variability in outcome measures, intervention types, and timing across the included studies, statistical pooling was not conducted. Although a meta-analysis is theoretically possible with as few as two sufficiently homogenous studies, no subgroup of studies demonstrated consistent enough characteristics to warrant this. Therefore, a narrative synthesis was used to summarize the findings. The decision was based on methodological and clinical heterogeneity, as per JBI and PRISMA guidance. Descriptive tables, figures, and graphs were used to present this data effectively.

3.7.1 Reporting of the Strength of Evidence

Since meta-analysis was deemed unfeasible, the GRADE (Grades of Recommendation, Assessment, Development, and Evaluation) approach was not utilized. The level of confidence was derived from the critical appraisal of each study included in the review, with the quality of studies reported as low, medium, or high. The strength of evidence was evaluated based on methodological quality using the relevant JBI critical appraisal checklists. For randomized controlled trials (13 appraisal items), studies scoring 0–4 were classified as low quality, 5–9 as moderate quality, and 10–13 as high quality. For analytical cross-sectional studies (8 items), scores of 0–2 were considered low quality, 3–5 as moderate, and 6–8 as high quality.

These thresholds ensured consistency across study designs and allowed for structured interpretation of evidence strength. This assessment was conducted independently by the author and a second reviewer at the outcome level. No major disagreements arose during the process, so the involvement of a third reviewer was not required. Although some studies had minor details missing, sufficient information was available across all included papers, and it was therefore not necessary to contact any study authors for clarification.

3.8 Ethical Considerations

Since this study was a systematic review, no active human participants were required. An ethical waiver was requested through the University of the Witwatersrand Human Research Ethics Committee (Appendix D).

Any potential biases were eliminated by strictly adhering to the inclusion and exclusion criteria. In cases where a dispute arose between the two independent reviewers, a third reviewer was brought in to resolve the disagreement.

Chapter 4 Results

The following chapter provides interpretation of the findings of the study. The following were the objectives of the study:

- Compare the effectiveness of neuroplasticity and motor learning-based therapeutic interventions against traditional rehabilitation methods in athletes post-ACLR.
- Investigate the relationship between neuroplasticity, motor learning, RTP timelines, and reinjury rates in this population.

4.1 Study Inclusion

An overview of the search and selection process is provided in the PRISMA flow chart, Figure 2. A total of 1,837 references were identified from the search for both published and grey literature. After removing duplicate records and screening titles and abstracts, 87 records remained for full-text screening. Of these, 53 studies were included for full-text review despite lacking abstracts. Two study protocols were excluded because they did not report results; as protocols, they only outlined planned methodology and had not yet evaluated the effectiveness of any intervention, which is essential for inclusion in this review. Additionally, 57 studies were excluded due to ineligible participant characteristics; the inclusion criteria for this review required participants to be classified as "athletes," but most of these studies referred to their participants as "patients" or failed to provide sufficient clarity regarding the types of patients included. Ten studies were excluded for having ineligible study designs, seven were excluded due to ineligible interventions, and one study was excluded as it was a registered clinical trial still underway.

Appendix A lists the 81 studies that were excluded following full-text examination, along with the reasons for their exclusion. Six studies (Ahmadi et al., 2020; Arundale et al., 2017; Bartels et al., 2016; Ghaderi et al., 2021; Gholami et al., 2023; Kasmi et al., 2023) were critically appraised and included in the review despite their methodological limitations.

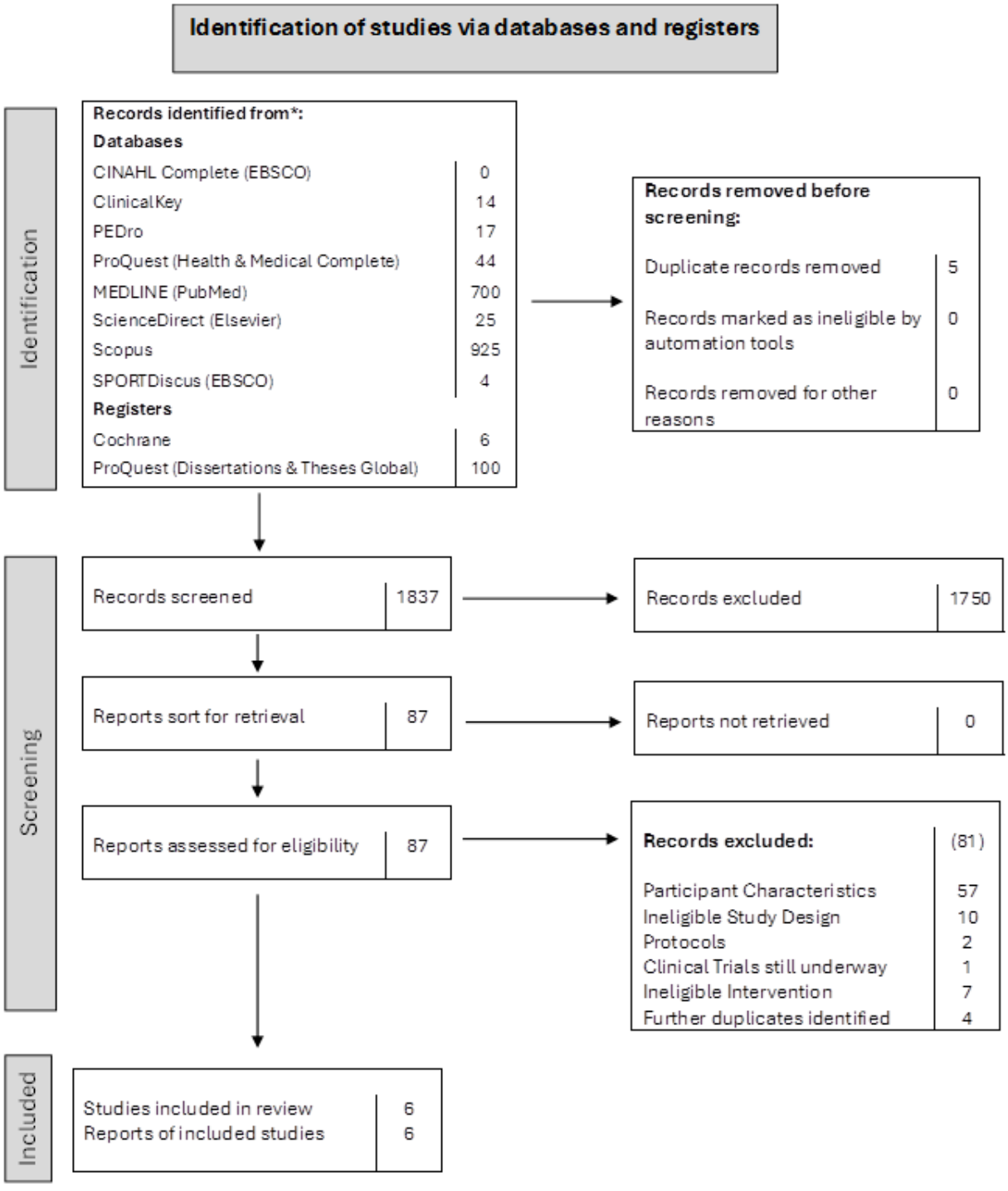

Figure 4: PRISMA flow diagram study selection process

4.2 Methodological Quality

The results of the quality assessment, using the Joanna Briggs System for the Unified Management, Assessment, and Review of Information (JBI SUMARI) appraisal tools for randomized controlled trials (RCT's) and analytical cross-sectional studies, are presented in Tables 1 and 2. The analytical cross-sectional study (Ahmadi et al., 2020) was classified as moderate to high quality. Among the five RCT's, three (Arundale et al., 2017; Gholami et al., 2023; Kasmi et al., 2023) were rated as moderate to high quality, one (Ghaderi et al., 2021) was deemed high quality, and the last (Bartels et al., 2016) was assessed as moderate quality.

In the critical appraisal, the term "unclear" was used instead of "no" to respond to specific questions, as the issues identified were primarily due to a lack of clarity or missing information rather than definitive shortcomings. A common criticism across all the studies included in this review was the absence of blinding for participants, assessors, and treatment providers. Blinding of participants and researchers was often not feasible in the included studies, particularly those involving rehabilitation and motor learning interventions. A key practical challenge is that therapists administering the intervention are inherently aware of the treatment type due to the active, manual, and cognitively engaging nature of the protocols. Similarly, participants can often discern whether they are receiving standard care or a novel intervention, especially when the intervention includes elements such as dual-task training or sensory perturbations. As noted by Boutron et al. (2007) and Yamato et al. (2016), this lack of blinding is a common limitation in physical therapy trials, increasing the risk of performance and detection bias. Nonetheless, it reflects the real-world constraints of clinical rehabilitation research.

4.2.1 Randomized Controlled Studies

Four of the five RCT's (Arundale et al., 2017; Ghaderi et al., 2021; Gholami et al., 2023; Kasmi et al., 2023) described their randomization methods. Among these, three studies (Arundale et al., 2017; Gholami et al., 2023; Kasmi et al., 2023) utilized computer-generated randomization, demonstrating true random allocation with concealment from the allocator. One study (Ghaderi et al., 2021) reported using a

random number table for randomization, conducted by an independent investigator unfamiliar with the testing protocol. Additionally, one study (Bartels et al., 2016) stated that participants were randomized, but did not provide further details regarding the randomization technique.

Only three studies (Arundale et al., 2017; Ghaderi et al., 2021; Gholami et al., 2023) blinded assessors to treatment allocation, while the remaining two studies (Bartels et al., 2016; Kasmi et al., 2023) did not clarify whether assessors were blinded, leaving the risk of detection bias uncertain. Bartels et al., (2016) indicated that "All tests were supervised by one examiner and a senior member of the study group," but did not specify if this examiner was blinded. Similarly, Kasmi et al.,(2023) mentioned that one of the assessors was an independent researcher not involved in the rehabilitation process but failed to confirm whether this assessor was blinded.

Notably, only one study (Ghaderi et al., 2021) reported that both participants and assessors were blinded. Two studies (Arundale et al., 2017; Gholami et al., 2023) did not clarify participant blinding but confirmed assessor blinding. In contrast, two studies (Bartels et al., 2016; Kasmi et al., 2023) did not report blinding for either participants or assessors. It is important to note that none of the five studies blinded the individuals delivering treatment, which is likely due to the physical nature of the interventions and the necessity for guidance during rehabilitation as previously mentioned.

All studies reported comparable intervention and control groups at study entry, although sample sizes were small, ranging from 24 to 50 participants, which affects the precision of estimates and increases the likelihood of failing to detect an effect. Two studies (Ghaderi et al., 2021; Kasmi et al., 2023) reported no attrition in their samples, with outcome measures documented for all participants pre- and post-intervention. Arundale et al. (2017) screened 113 athletes, enrolling 40 into the ACL-Specialized Post-Operative Return-to-Sports (ACL-SPORTS) training program, of which 36 had functional outcome data recorded at both the baseline and final post-intervention assessments. The authors noted an attrition of four participants over the course of the study and provided reasons for this loss. Bartels et al.,(2016) reported

no attrition; however, their tables displayed changing sample sizes across various clinical parameters without explanation. Gholami et al.,(2023) documented attrition of two participants at the final follow-up post-intervention, also providing reasons for this loss.

Outcomes were measured uniformly across all intervention groups in the five controlled studies (Arundale et al., 2017; Bartels et al., 2016; Ghaderi et al., 2021; Gholami et al., 2023; Kasmi et al., 2023), with most studies assessing lower limb muscle strength, balance, and functional performance using single- or triple-hop tests. However, one study (Bartels et al., 2016) did not provide references or evidence supporting the reliability and validity of its chosen outcome measures. Consequently, while data from this study were included in the review, the results were analysed and interpreted with caution.

4.2.2 Analytical cross-sectional studies

The study by Ahmadi et al.,(2020) exhibited only one notable area of bias, specifically a lack of information regarding potential confounding factors. The authors did not mention any confounding factors in their study, nor did they provide an explanation of the strategies employed to address them. Under the limitations section, they acknowledged uncertainty about what participants focused on during the control condition, which could be regarded as a potential confounding factor. However, no further efforts to mitigate this uncertainty were discussed. While the study subjects were well-defined, details about the study setting were sparse. Both the exposure and outcomes were valid and measured reliably, with references provided by the authors for their chosen measurement tools.

A comparison between the studies by Bartels et al.,(2016) and Ghaderi et al.,(2021) highlights differences in methodological rigor. The study by Ghaderi et al.,(2021) demonstrated strong methodological rigor, which enhances the credibility of its results compared to those of Bartels et al.,(2016) in this review. Although the critical

appraisal rating for Bartels et al.,(2016) was classified as medium level evidence, the study exhibited significant gaps in information across several areas.

Table 1. Critical Appraisal of Eligible Analytical Cross-sectional Study

Citation	**Q1** Inclusion criteria clearly defined	**Q2** Study subjects and setting described in detail	**Q3** Exposure measured in valid and reliable way	**Q4** Objective standardized criteria used for measurement of the condition	**Q5** Confounding factors identified	**Q6** Strategies to deal with confounding factors stated	**Q7** Outcomes measured reliably	**Q8** Appropriate statistical analysis	**Total**
Ahmadi P, Salehi R, Mehravar M, Goharpey S, Negahban H. 2020.	Y	Y	Y	Y	U	U	Y	Y	6/8
%	100.0	100.0	100.0	100.0	0.0	0.0	100.0	100.0	

U = Unclear; Y = yes

Critical appraisal scores:

- 0-2 = low quality of evidence
- 3-5 = medium quality of evidence
- 6-8 = high quality of evidence

Table 2. Critical Appraisal of Eligible Randomized Controlled Trial

Citation	Q1 True randomization	Q2 Allocation concealed	Q3 Groups similar at baseline	Q4 Participants blinded	Q5 Those delivering treatment blinded	Q6 Assessors blinded	Q7 Treated identically	Q8 Follow-up complete	Q9 Participants analysed in groups to which they were randomized	Q10 Same outcomes	Q11 Reliably measured	Q12 Appropriate statistical analysis	Q13 Trial design appropriate	Total
Gholami F, Letafatkar A, Moghadas Tabrizi Y, Gokeler A, Rossettini G, Ghanati HA, et al. 2023.	Y	Y	Y	U	U	Y	Y	Y	Y	Y	Y	Y	Y	10/13
Kasmi S, Sariati D, Hammami R, Clark CCT, Chtara M, Hammami A, et al. 2023.	Y	U	Y	U	U	U	Y	Y	Y	Y	Y	Y	Y	9/13
Bartels T, Proeger S, Brehme K, Pyschik M, Delank KS, Schulze S, et al. 2016.	U	U	Y	U	U	U	Y	Y	Y	Y	U	Y	U	6/13
Ghaderi M, Letafatkar A, Thomas AC, Keyhani S. 2021.	Y	Y	Y	Y	U	Y	Y	Y	Y	Y	Y	Y	Y	12/13
Arundale AJH, Cummer K, Capin JJ, Zarzycki R,	Y	U	Y	U	U	Y	Y	Y	Y	Y	Y	Y	Y	10/13

Snyder-Mackler L. 2017.														
%	80	40	100	20	0.0	60	100	100	100	100.0	80	100.0	80	

U = Unclear; Y = yes

Critical appraisal scores:

- 0-4 = low quality of evidence
- 5-9 = medium quality of evidence
- 10-13 = high quality of evidence

4.3 Characteristics of included studies

The key characteristics of the six included studies (Ahmadi et al., 2020; Arundale et al., 2017; Bartels et al., 2016; Ghaderi et al., 2021; Gholami et al., 2023; Kasmi et al., 2023) are detailed below, categorized where appropriate into controlled and analytical cross-sectional studies. A summary of these characteristics by study can be found in Appendix C.

4.3.1 Types of Studies

Among the six studies, five were RCT's. Three of these studies (Arundale et al., 2017; Gholami et al., 2023; Kasmi et al., 2023) described the use of computer-generated randomization methods. One study (Ghaderi et al., 2021) utilized a random number table conducted by an independent investigator, while another study (Bartels et al., 2016) merely stated that participants were randomized. The sixth study (Ahmadi et al., 2020) was an analytical cross-sectional study.

4.3.2 Participants and Setting

The studies were conducted across various locations: three studies (Ahmadi et al., 2020; Ghaderi et al., 2021; Gholami et al., 2023) were carried out in Iran, one in Tunisia (Kasmi et al., 2023), one in Germany (Bartels et al., 2016), and one in the USA (Arundale et al., 2017). Sample sizes were small across all included studies, ranging from 24 to 50 participants.

Information regarding the study settings was limited. One study (Ghaderi et al., 2021) provided no context about the setting, while two others (Ahmadi et al., 2020; Bartels et al., 2016) offered minimal details. Ahmadi et al.,(2020) focused on athletes and soccer players, while Bartels et al.,(2016) described the SpeedCourt-Interactive training device developed in Hemsbach, Germany, which was investigated for its effectiveness as an alternative to traditional sensomotoric training. The study by Gholami et al.,(2023) took place in the biomechanics lab at Kharazmi University, Iran, from March to July 2020. The study by Kasmi et al.,(2023) involved elite male athletes from various sports who had sustained ACL injuries and undergone surgery at the Hospital Ortopedico in Tunisia, performed by two knee surgeons with 20 years

of experience in ACL reconstructions. Lastly, the study by Arundale et al.,(2017) introduced the Anterior Cruciate Ligament-Specialized Post-Operative Return-to-Sports (ACL-SPORTS) training program, aimed at preparing athletes for a successful return to preinjury activities, enhancing limb symmetry, and addressing postoperative neuromuscular impairments and predictors of a second knee injury. In the United States, it is common for athletes post-ACL reconstruction to be discharged from physical therapy upon achieving basic daily living goals and athletic tasks like running. Rehabilitation before the ACL-SPORTS training program was not standardized and occurred across various community physical therapy clinics.

All studies involved participants who were athletes engaged in competitive sports. Three studies (Ahmadi et al., 2020; Gholami et al., 2023; Kasmi et al., 2023) provided specific details about the types of sports their participants were involved in. Two studies (Arundale et al., 2017; Kasmi et al., 2023) discussed the demands of their participants' sports in terms of training hours prior to surgery. Four studies (Arundale et al., 2017; Bartels et al., 2016; Ghaderi et al., 2021; Gholami et al., 2023) indicated the timing of ACL surgery in relation to the commencement of the study intervention, along with details about the type of surgery performed and the surgeon involved. In the analytical cross-sectional study, healthy subjects (who were also athletes matched by age and sport) were compared with ACLR athletes based on age, height, weight, activity level, education level, and leg dominance. In the controlled studies, all intervention and control groups were matched at baseline. Only Arundale et al.,(2017) utilized a sample group of participants who had completed three to nine months of outpatient rehabilitation. For additional information on the participants and study settings, refer to the appendix C containing the characteristics of the included studies in tabulated form.

4.3.3 Interventions and Comparators

The studies exhibited heterogeneity in treatment methods and protocols. A summary of the interventions and protocols tested is presented in Table 3, with further details available in Appendix C.

Only three studies (Ahmadi et al., 2020; Ghaderi et al., 2021; Gholami et al., 2023) provided sufficient detail to allow for replication of the intervention methods; the other

three studies (Arundale et al., 2017; Bartels et al., 2016; Kasmi et al., 2023) required readers to make assumptions regarding various aspects of the treatment provided. Three studies (Ghaderi et al., 2021; Gholami et al., 2023; Kasmi et al., 2023) specified that interventions were guided by experienced athletic trainers or expert strength and conditioning coaches, whereas the remaining three studies (Ahmadi et al., 2020; Arundale et al., 2017; Bartels et al., 2016) either did not report this information or provided vague details. All studies, however, offered adequate information on the duration and frequency of the interventions.

Table 3. Interventions in included studies

Intervention name	Components of intervention	Duration and frequency of intervention	Delivered by	Comparator	Outcomes measured	Measurement Method	Study/Citation
External focus of attention	Eight exercises were performed as part of the program. For each exercise, the athletic trainer would provide an instruction/cue intended to promote an external focus of attention (shown in bold font). The exercises and their relevant cues are listed below: 1) Double-leg squats: **While bending your knees, point your knees toward the cones and pretend you are going to sit on a chair while keeping a ball between your knees** **2)** Walking lunges: **While pretending you have a plank on your back, point your knee toward an imaginary point in front of you.** **3)** Single-leg squats: **Stand on one leg and reach slowly toward the cone with your knee while bending your knee.** **4)** Double-leg drop jumps: **Jump down from the box, land on the markers on the floor, and point your toes and knees toward the cones.** **5)** Single-leg stance on an unstable surface: **Keep the bar horizontal**	Athletes completed 3 sessions per week for weeks 1-6 and 2 sessions per week for weeks 7 and 8 (22 total sessions)	The 'third' experienced athletic trainer involved in the study.	Routine activities which focused on sport-specific skills training over the same 8-week period but did not receive any targeted neurocognitive components.	1)Biomechanics testing 2)Patient-reported function	1) •Kinematic data: Peak trunk flexion, peak hip flexion, peak knee flexion, peak knee abduction, peak knee internal rotation) •Kinetic data: Peak reaction force, peak anterior tibial shear force, peak knee extension moment, peak knee abduction moment, loading rate •Knee joint position sense (using isokinetic dynamometer) 2)Persian version of the IKDC form	(Ghaderi et al., 2021)

	6) Single-leg countermovement jumps: **Jump as high as you can and touch the hanging ball** **7)** Horizontal bounds: **Push against the ground as forcefully as possible.** **8)** Single-leg standing long jumps: **Try to jump past the line** All exercises were performed with bodyweight resistance.						

	Postural control was evaluated using a force plate and a Thera Band Black Wobble Board was placed on the force plate to evaluate postural control in a dynamic situation. A smartphone equipped with a planar levelling application on the wobble board center projected the phone screen of a 51" LCD at an eye level 3m in front of the subjects. The levelling application provided the external focus through visual feedback. The participants were asked to stand on their operated leg and focus on minimizing the movement of the bubble marker at the origin of coordinates. Using an application image on the screen would increase the adherence of the subjects to keep their focus on the bubble marker's movement.	Before the test, the participants performed one familiarization trial (60s) in every condition. To evaluate postural control, the participants were asked to stand on their operated leg (60s) with full-extended knee and arms hanging on the sides such that the contralateral leg was semi-flexed.	Not clear. "We used a Thera Band black Wobble Board placed on the force plate to evaluate postural control in a dynamic situation." The "we" may be referring to the researchers themselves, but no clarity is given on this.	Normal control of their balance while standing on a wobble board.	•Static standing balance •Dynamic Postural Sway	Dependent variables included area of 95 % confidence ellipse, standard deviation (SD) of COP in anterior-posterior (AP) and medial-lateral (ML) directions, mean velocity of COP in AP and ML directions, and Mean Power Frequency (MPF) in AP and ML directions. These variables were used to measure linear centre of pressure in order to assess	(Ahmadi et al., 2020)

Continuous Cognitive Task	The participants were asked to stand on a single leg with their eyes fixed at an eye level target 3m ahead while performing a sequence continuous task. The sequence continuous task comprised of mentally counting the number of times a randomly selected digit (1–9) was occurred in 20 sets of three-digit numbers each presented at a 3-second interval (e.g. count the number of times 2 was occurred in the following sequences: 221, 326, 471, etc.) After the test the participants provided the answer. If the error score was 3 or greater, the trial was redone. To reduce the chance of memorization, three-digit sequences and preselected digit were changed in every trial. The use of fingers for counting was prohibited to maintain maximal cognitive effort.	Both the external focus of attention condition and the continuous cognitive task condition were repeated 3 times.				static standing balance and dynamic postural sway.	
Differential training	The differential training exercises had internal and external variants as components of this intervention. Variations of the double-legged jump were included as follows: 1) Double-legged jump on a bosu-ball 2) Double-legged jump over an obstacle 3) Double-legged jump with an air target The **internal variants** that related to cognition/coordination-orientated exercises were as follows: **Before jumping:** - 2–3 bunny hops	Exercises executed for 8 weeks under the supervision of an experienced athletic trainer. Each week comprised three sessions of 25-30 min on odd days.	According to the group assignment, a researcher/experienced athletic trainer blinded to the baseline assessments proceeded with training.	Typical training regimen, such as improving technique and sport-related skills.	1)Functional performance 2)Dynamic balance during the 3)Biomechanics testing 4)Kinesiophobia	1)Triple hop test 2)Star Excursion Balance Test 3)Single leg drop jump (knee flexion (KF), ankle dorsiflexion (AD), knee valgus (KV), and vertical ground reaction force (VGRF) 4)Tampa Scale of Kinesiophobia	(Gholami et al., 2023)

	- skipping both/left/right leg - high knees both/left/right knee - butt-kicks both/left/right leg - zigzag - shuffle to the left, right - complete turn to left/right before you jump **While jumping:** - arms crossing in front of the chest, behind the back, - raise both/left/right arm - circle both/left/right arm - head to left/right - close left/right eye **While landing:** - one arm in front and the other arm behind - landing with a very wide/narrow stance - landing on toes The **internal variants** that related to metabolism/mentally oriented exercises were as follows: **Fatigue:** - With—Without The **external variants** with primary stimulations of sensory system (apperception) were as follows: **Visual:** - in a virtual reality - environment **Somatosensory:** - exercise on sand - with or without shoes **Proprioceptive:** - exercise in dark - with weight vest **Acoustic:** - loud music						

	- noise from the audience						
Visuomotor training	VMT protocols were developed for stroboscopic intervention and integrated into regular training. The athletes performed the protocol under stroboscopic conditions. Each week the shutter glasses' settings were adjusted to compensate for expected improvements in visuomotor performance and to avoid adaptation to a specific setting. The VMT protocols consisted of 6 different tasks with specific visual cues(shown in bold font), including: 1) A Tap-test: • **Tap the cones (Acoustic cue)** • The Tap-test requires the athlete to run 10 m to tap a cone, cut to the right or left for 5 m to tap another cone, cut to the opposite direction for 10 m to tap the third cone, return to the center by cutting 5 m to tap the first cone and then run 10 m back to the start position—thereby running in a "T" formation). A modification that increases the difficulty of this task and simulates the cognitive demands of sport is to have the clinician call out "Left" or "Right" to indicate which direction the athlete should cut prior to reaching the first cone,	8-week training period, consisting of three sessions per week (even days), with every training session lasting approximately 25-30 min.					

	thereby creating an unanticipated cutting task which has been previously associated with increased injury-risk biomechanics compared to anticipated trials 2) Agility ladder drills • **The confines of the ladder** • Agility ladder drills require athletes to match specific foot-placement patterns within an agility ladder context. 3) Single-leg Deadlifts • **Place an object by the cone(s)** • Single-leg deadlifts may be modified by requiring athletes to gently place a small object on the ground next to a cone target. To increase the difficulty, multiple cones can be placed at different angles within the athlete's field of view, set at distances equal to his or her max volitional reaching distance while standing on one leg. For example, if the clinician chooses to use three targets, then he or she may call out "Left", "Center", or "Right" to vary the task order and difficulty 4) Single-leg stance (on foam) • **Hold the bar horizontally** • Single-leg stance on a foam surface may be modified by having the participant hold a						

	light-weight bar with an outstretched arm and focus on keeping it steadily horizontal 5) Vertical jumps • **Hit the overhead target** • The VERTEC is a therapeutic tool that assesses maximum vertical jump height by requiring athletes to jump and hit an overhead target. While using the VERTEC to have athletes hit the mark equal to 80% of their maximal jump height, clinicians may call out “Left” or “Right” during the initial flight phase of the jump to signal to the athlete to unilaterally land on his or her left or right leg. The use of spontaneous cuing creates an unanticipated landing task, which has been previously associated with increased injury-risk biomechanics compared to anticipated landing. 6) Squat jumps • **Land facing the cones** • Jump squats may be modified by placing four cones around the participant at 0, 90, 180, and 270-degree positions. After numbering each cone one through four, the clinician may then rapidly call out cues to the athlete to specify which cone they should face						

	after each jump squat. To increase the difficulty of this cognitive challenge, the clinician can introduce more cones or increase the rapidity of cuing.						
Combination of eccentric and plyometric	Two weeks after surgery and 12 weeks before the intervention period, all participants received the same rehabilitation protocol consisting of edema and inflammation control, expansion of the range of motion, improvement of stability, and strength training. The interventions were: 1) Single-mode eccentric training 2) Single-mode plyometric training 3) Combined eccentric and plyometric training No further information was provided about the components or specifics of the interventions.	All participants performed two weekly training sessions over a 6-weeks intervention period with 60 min per session and an overall number of 12 training sessions in addition to the traditional program. The training volume (training weeks, sets, repetitions, and duration) was equal between the intervention group and the control groups. Each training session started with a standardized 15-minute warm-up, including submaximal intensity	Training was delivered by expert strength and conditioning coaches from the National Medical Sports Center of Tunisia.	Traditional rehabilitation program consisting of flexibility, balance (i.e., bipedal and unipedal stance) and submaximal running exercises	1)Psychological kinesiophobia status 2)Patient reported function 3) Functional assessment	1) Tampa kinesiophobia score 2) (KOOS score and IKDC score) 3) Isokinetic muscle strength performance (LSI, Peak torque (PT), the total work (TW) & ratio- HQ, ratio - TW at different angular velocities measured in knee flexors and extensors by isokinetic testing)	(Kasmi et al., 2023)

		running, dynamic stretching, calisthenics, and preparatory exercises (eg. Balance and landing, squatting, jumping exercises) at a progressively increased intensity.					
SpeedCourt Training	The SpeedCourt training consisted of 5–6 exercises which lasted between 15 and 30s. Every exercise was repeated thrice. The pause lengths showed inter-individual differences depending on the resilience of the patient. Generally the pause lengths were four times as long as the original exercise. The exercises comprised mostly running actions which were incidentally computer generated. Some of them were also colour coded, which were matched to different tasks (yellow: jog twice around the field; blue: run to the opposite field).	The training (I & C) lasted for a duration of 3 weeks, twice a week.	Not reported	The stabilization training was standardized. Different unstable and uneven surfaces were incorporated (Posturomed, Slashpipe, BOSU, Airex, Kippelbrett, Pezziball, Stepper). Every exercise was completed in 30 s. A 30-s pause was allowed and then the exercise was performed with the contralateral side. During every training,	1) Anthropometric parameters 2) Functional Assessment	1) The dimensions of the upper and lower leg were measured. This was conducted using metric tape 15 and 10 cm above, at 15 and 10 cm below joint-line. 2) •Total range of motion in flexion and extension (tROM) •Finger-ground distance •Reaction time •Ground contact time •Tapping (time interval 3sec) •Jump height (uni- and bi-lateral) •Jump width (bilateral).	(Bartels et al., 2016)

				30 min consisted of the exercises for stabilization.			
Perturbation training	The Anterior Cruciate Ligament-Specialized Post-Operative Return-to-Sports (ACL-SPORTS) training program was derived from successful primary ACL injury prevention techniques. The primary program is multimodal and includes strengthening, agility, plyometric and prevention-focused exercises. Perturbation training, a neuromuscular reeducation technique was added to this primary program to form the intervention of interest in this study. The components of the intervention are as follows: 1) Progressive secondary ACL injury prevention exercises and agility drills 2) Quadriceps femoris muscle strengthening for athletes whose quadriceps strength symmetry measures were between 80% and 90% to help athletes achieve the return to sport criteria of 90% quadriceps strength limb symmetry 3) Perturbation training No further details of specific exercises were given for the components listed above.	The ACL SPORTS training program included 10 treatment sessions (two times per week for 5 weeks) for all athletes.	Not reported	SAP (strengthening, agility, prevention): The SAP group received progressive secondary ACL injury prevention exercises and agility drills. Quadriceps femoris muscle strengthening exercises were also included for athletes whose quadriceps strength symmetry measures were between 80% and 90% to help athletes achieve the return to sport criteria of 90% quadriceps strength limb symmetry [40]. Collectively, these exercises were determined to	1)Functional assessment 2)Patient reported function	1) •Quadriceps strength (electromechanical dynamometer) •Quadriceps strength limb symmetry •Limb symmetry indices (LSI) •Single-legged hop testing 2) •IKDC form •KOOS-Sports and recreation subscale •KOOS-quality-of-life subscale	(Arundale et al., 2017)

				target impairments in balance, dynamic sport-related tasks, and muscle strength, all of which are risk factors for initial ACL injury [29, 30] and subsequent reinjury.			

Abbreviations: ACL = Anterior Cruciate Ligament; RCT = Randomised Controlled Trial; RTP = Return to Play; IKDC = International Knee Documentation Committee; KOOS = Knee Injury and Osteoarthritis Outcome Score; VAS = Visual Analogue Scale; YBT = Y-Balance Test; SLH = Single-Leg Hop; SEBT = Star Excursion Balance Test; EMG = Electromyography; ROM = Range of Motion; MVIC = Maximal Voluntary Isometric Contraction; NR = Not Reported; SD = Standard Deviation.

4.3.3.1 External Focus of Attention (EF)

Two studies investigated training with an EF: one was a RCT (Ghaderi et al., 2021) and one analytical cross-sectional study (Ahmadi et al., 2020). Due to the heterogeneous study designs, direct comparisons between the studies are challenging, as each employed different EF protocols and comparators.
Ahmadi et al.,(2020) compared the effects of an EF against an alternative intervention and a control condition, assessing their impact on postural sway and static standing balance. The sample included participants who had undergone ACL reconstruction, alongside healthy individuals. In contrast, the study by Ghaderi et al.,(2021) involved two groups of participants who had all undergone ACL reconstruction but received different interventions. The control group continued with their traditional neuromuscular training program, while the intervention group engaged in the same training, supplemented with cues to direct an EF. This study aimed to determine whether eight weeks of training—using identical exercises as the control group but incorporating external focus cues—would affect biomechanics, knee proprioception, and patient-reported function in athletes recovering from ACL reconstruction. Specific cues used to direct the EF are detailed in Table 3.

In the first phase of the study by Ghaderi et al.,(2021), participants completed three sessions per week during weeks 1 to 6, followed by two sessions per week in weeks 7 and 8. All interventions were guided by an experienced athletic trainer.
The study by Ahmadi et al.,(2020) highlighted that postural control, achieved through automatic processes rather than active cognitive attention, is a critical factor in determining an athlete's readiness to return to sport and could play a role in preventing reinjury. Therefore, their research focused on attentional strategies and movement automaticity, specifically comparing the effects of an EF with those of a continuous cognitive task (CCT) on postural stability following ACL reconstruction. The CCT will be discussed in the subsequent subsection. The investigators utilized a force plate to evaluate postural stability under the three conditions. Given the study design, there was no intervention period; rather, the study assessed the effects of these conditions at a specific point in time.

4.3.3.2 Continuous Cognitive Task

A cognitive task is incorporated into an exercise as an additional strategy to divert attention from postural control. In the study by Ahmadi et al.,(2020) the authors opted for a CCT, which consistently diverts focus away from postural control, as opposed to discrete cognitive tasks that allow for intermittent attention to postural stability. This analytical cross-sectional study was unique in reporting the effects of such an intervention. As previously discussed, the aim of the study was to examine the effects of this cognitive task on postural sway compared to a control condition and an EF condition. The participants were asked to engage in a task that involved mentally counting the number of times a randomly selected digit appeared in a sequence of numbers presented at three-second intervals. This task required participants to utilize cognitive resources, effectively diverting their attention from postural control.

4.3.3.3 Differential Learning (DL)

Only one study in this review explored the benefits of DL. Gholami et al.,(2023) conducted an RCT in which participants engaged in DL exercises for eight weeks under the supervision of an experienced athletic trainer. Each week consisted of three sessions lasting 25 to 30 minutes, focusing on three variations of a double-legged jump that utilized both internal and external variants to enhance the differential aspect of the training. Table 3 provides detailed descriptions of these two components of the intervention. In contrast, the control group followed a traditional training regimen aimed at improving technique and sport-related skills. The study aimed to compare the effects of DL and visuo-motor training (VMT) against the control group receiving traditional treatment on functional performance, biomechanical factors, and psychological outcomes in athletes with a history of ACLR. The VMT intervention will be discussed further below.

4.3.3.4 Visuo-motor Training

The study conducted by Gholami et al.,(2023) was the only one in this review to report on the effectiveness of VMT. This intervention utilized the same dosage and frequency as the DL exercises. However, in this case, athletes performed six different tasks while wearing stroboscopic glasses and following specific verbal cues. Each

week, the opacity of the glasses was gradually increased to enhance the visual obstruction during the exercises.

4.3.3.5 Combination of Eccentric and Plyometric (COMB)

Only one study investigated the benefits of this combined training approach (Kasmi et al., 2023). The purpose of this study was to examine the effects of six weeks of combined eccentric-plyometric training compared to single-mode eccentric and single-mode plyometric training during the rehabilitation of elite male athletes from various sports after ACL reconstruction. In this controlled trial, participants began their assigned intervention 14 weeks post-surgery. Until that point, all participants followed the same rehabilitation protocol, which focused on oedema and inflammation control, range of motion, stability improvement, and strength training.

Following this initial phase, all participants engaged in two training sessions per week over a six-week intervention period, totalling 12 training sessions, in addition to their traditional rehabilitation program. The training volume (including weeks, sets, repetitions, and duration) was kept consistent across all groups. Each session began with a standardized 15-minute warm-up, consisting of submaximal running, dynamic stretching, calisthenics, and preparatory exercises performed at progressively increased intensity. While the warm-up was described in detail, specific information regarding the exercises included in the actual intervention was not provided. The authors did note that the training was conducted by expert strength and conditioning coaches. The comparator in this study was a traditional rehabilitation program that included flexibility, balance, and submaximal running exercises.

4.3.3.6 SpeedCourt Training

SpeedCourt training is an interactive system designed to train athletes to respond to very short muscular reactions, specifically those with a latency of less than 200 milliseconds. Developed in Germany, this technological device covers an area of 7m x 7m and aims to enhance explosive acceleration, position-specific changes of direction, coordinative skills, and cognitive functions related to motor activities. The

controlled trial conducted by Bartels et al.,(2016) was the only study in this review that reported on the benefits of this intervention. The authors aimed to determine whether rehabilitation incorporating unexpected disturbance programs, such as those offered by the SpeedCourt device, which focuses on short latency responses, provides benefits over traditional neuromuscular training after ACL reconstruction.

The SpeedCourt training involved 5 to 6 computer-generated running exercises lasting between 15 and 30 seconds, each repeated three times. Some of these exercises were color-coded and aligned with different motor tasks. The training regimen lasted for three weeks, with sessions occurring twice a week. While a general overview of the intervention was provided, the details necessary for accurate replication in clinical or experimental settings were insufficient. The comparator used in this study was basic stabilization training. Table 3 provides additional information about this training. However, the authors did not specify who delivered the SpeedCourt training or the comparator.

4.3.3.7 Perturbation Training

One study in this review, conducted by Arundale et al.,(2017), investigated the benefits of incorporating perturbation training into ACL rehabilitation. The objective of this controlled trial was to assess whether the inclusion of perturbation techniques would lead to improvements in functional outcomes and limb symmetry.

In this study, perturbation training was added to the Anterior Cruciate Ligament-Specialized Post-Operative Return-to-Sports (ACL-SPORTS) training program, which was developed based on effective primary ACL injury prevention strategies. The primary program is multimodal, incorporating strengthening, agility, plyometric, and prevention-focused exercises. For further specifics on these exercises, please refer to Table 3. However, the study did not provide details on how the perturbation training was implemented or who delivered the training instructions. The ACL-SPORTS training program consisted of 10 treatment sessions, scheduled twice a week over a duration of 5 weeks for all participating athletes.

4.3.4 Outcomes

A summary of the outcomes assessed in the studies is presented in Table 4. None of the studies reported specific training for the assessors. However, two studies (Arundale et al., 2017; Gholami et al., 2023) confirmed that the outcome assessors were blinded. Two other studies (Ahmadi et al., 2020; Kasmi et al., 2023) did not provide details about the assessors, while Bartels et al.,(2016) specified that tests were supervised by a single examiner, a senior member of the study group. In the study by Ghaderi et al.,(2021) a second licensed athletic trainer conducted the baseline assessments, but it was unclear who performed the follow-up assessments.

The primary outcome of this review is the RTP timeframe. The most common outcome measures used across the six studies included biomechanical testing, functional assessments, static balance, dynamic postural sway, patient-reported function, and psychological kinesiophobia status. Two studies (Ahmadi et al., 2020; Gholami et al., 2023) reported changes in static balance and dynamic postural sway. Four studies (Arundale et al., 2017; Bartels et al., 2016; Gholami et al., 2023; Kasmi et al., 2023) documented changes in various functional tests. Additionally, two studies (Ghaderi et al., 2021; Gholami et al., 2023) reported changes in biomechanical testing, while two studies (Gholami et al., 2023; Kasmi et al., 2023) indicated changes in psychological kinesiophobia scores. Lastly, three studies (Arundale et al., 2017; Ghaderi et al., 2021; Kasmi et al., 2023) reported changes in patient-reported function.

As outlined in Section 3.2.3, the review's primary and secondary outcomes — RTP timeframe and risk of reinjury — were not always directly reported in the included studies. Instead, these were inferred through interpretation of reported outcome measures such as strength, hop performance, neuromuscular control, and functional test results. This interpretative process allowed consistency across studies and has been carried forward into the synthesis of results.

Table 4. Outcomes measured in included studies

Study/citation	Domain	Outcomes Measured	Approach
(Ghaderi et al., 2021)	1) Return to play timeframe 2) Incidence of reinjury	Biomechanics Testing	•Kinematic data: Peak trunk flexion, peak hip flexion, peak knee flexion, peak knee abduction, peak knee internal rotation) •Kinetic data: Peak reaction force, peak anterior tibial shear force, peak knee extension moment, peak knee abduction moment, loading rate •Knee joint position sense (using isokinetic dynamometer)
(Gholami et al., 2023)			Single leg drop jump (knee flexion (KF), ankle dorsiflexion (AD), knee valgus (KV), and vertical ground reaction force (VGRF)
(Gholami et al., 2023)		Functional Performance	Triple hop test
(Kasmi et al., 2023)			Isokinetic muscle strength performance (LSI, Peak torque (PT), the total work (TW) & ratio- HQ, ratio -TW at different angular velocities measured in knee flexors and extensors by isokinetic testing)
(Bartels et al., 2016)			•Total range of motion in flexion and extension (tROM) •Finger-ground distance •Reaction time •Ground contact time •Tapping (time interval 3sec) •Jump height (uni- and bi-lateral) •Jump width (bilateral).
(Arundale et al., 2017)			•Quadriceps strength (electromechanical dynamometer) •Quadriceps strength limb symmetry •Limb symmetry indices (LSI) •Single-legged hop testing
(Ahmadi et al., 2020)		Static standing balance and dynamic postural sway	Dependent variables included area of 95 % confidence ellipse, standard deviation (SD) of COP in anterior-posterior (AP) and medial-lateral (ML) directions, mean velocity of COP in AP and ML directions, and Mean Power Frequency (MPF) in AP and ML directions. These variables were used to measure linear centre of pressure in order to assess static standing balance and dynamic postural sway.
(Gholami et al., 2023)			Star Excursion Balance Test
(Ghaderi et al., 2021)		Patient-reported function	Persian version of the IKDC form
(Kasmi et al., 2023)			KOOS score and IKDC score
(Arundale et al., 2017)			•IKDC form •KOOS-Sports and recreation subscale •KOOS-quality-of-life subscale
(Gholami et al., 2023)		Psychological kinesiophobia status	Tampa Scale of Kinesiophobia
(Kasmi et al., 2023)			Tampa kinesiophobia score
(Bartels et al., 2016)		Anthropometric parameters	The dimensions of the upper and lower leg were measured. This was conducted using metric tape 15 and 10 cm above, at 15 and 10 cm below joint-line.

Various measurement methods were used to determine biomechanical changes, including kinematic data (Ghaderi et al., 2021; Gholami et al., 2023), kinetic data (Ghaderi et al., 2021; Gholami et al., 2023), and knee joint position sense (Ghaderi et al., 2021). Patient-reported function was assessed using KOOS scores (Arundale et al., 2017; Kasmi et al., 2023) and IKDC scores (Arundale et al., 2017; Ghaderi et al., 2021; Kasmi et al., 2023). Psychological kinesiophobia scores were measured by the Tampa Scale of Kinesiophobia (Gholami et al., 2023; Kasmi et al., 2023). Ahmadi et al.,(2020) used linear centre of pressure to assess static balance and dynamic postural sway, while Gholami et al.,(2023) employed the Star Excursion Balance Test (SEBT) for dynamic balance. Functional testing varied across studies and included measurements such as triple hop distance, isokinetic muscle strength, total knee range of motion, reaction and ground contact times, jump height and width, limb symmetry, and single leg hop tests. Table 4 provides additional details on these measurement methods.

The analytical cross-sectional study (Ahmadi et al., 2020) employed validated and reliable measurement methods, with supporting references. Four RCT's (Arundale et al., 2017; Ghaderi et al., 2021; Gholami et al., 2023; Kasmi et al., 2023) used reliable and valid methods, though the data was comparable rather than interchangeable. The fifth study (Bartels et al., 2016) lacked details on the reliability and validity of its measurement methods, though one reference was provided to support the use of the SpeedCourt device for assessing reaction time, ground contact time, tapping, and jump performance.

Biomechanical outcomes were reported using pre- and post-intervention mean and standard deviation values of kinematic and kinetic measurements, with effect sizes (Ghaderi et al., 2021; Gholami et al., 2023). Ghaderi et al.,(2021) also presented the percentage change from baseline to follow-up across variables, with data tables comparing all study groups. Functional outcomes were reported in various formats, including mean and standard deviation for the triple hop test (Gholami et al., 2023), effect size for peak torque ratios (Kasmi et al., 2023), mean limb symmetry scores (Arundale et al., 2017), and a range of functional measures (Bartels et al., 2016), with all results provided in table format.

Standing balance and dynamic postural sway were reported in mean scores for both groups under three conditions in the study by Ahmadi et al.,(2020). Gholami et al.,(2023) reported pre- and post-intervention mean and standard deviation for the SEBT distance. These measurements are not directly comparable.

Patient-reported function outcomes were consistently reported across three studies (Arundale et al., 2017; Ghaderi et al., 2021; Kasmi et al., 2023) using versions of the IKDC Knee Evaluation Form, commonly used for assessing knee-related function post-ACLR. Arundale et al.,(2017) and Ghaderi et al.,(2021) used the Persian version, with scores expressed as percentages, and reported pre- and post-intervention scores, relative change, and effect size. Arundale et al.,(2017) displayed IKDC scores in graph format across time points but did not specify the IKDC version. Arundale et al.,(2017) and Kasmi et al.,(2023) used the IKDC 2000, which converts ratings to a 100-point scale, with mean, standard deviation, and relative change reported pre- and post-intervention.

Two studies (Arundale et al., 2017; Kasmi et al., 2023) used KOOS scores for patient-reported function. The KOOS is a 42-item, self-administered questionnaire with five subscales scored separately from 0 to 100, where 100 indicates no problems. Kasmi et al.,(2023) reported mean KOOS scores and standard deviation pre- and post-intervention. Arundale et al.,(2017) reported two KOOS subscales—Sports and Recreation, and Quality of Life—using graphs at two post-intervention time points.

Psychological kinesiophobia was measured in two studies (Gholami et al., 2023; Kasmi et al., 2023) using the Tampa Scale of Kinesiophobia. Kasmi et al., (2023) reported pre- and post-intervention TSK-CF scores with mean, standard deviation, and relative change. Gholami et al.,(2023) used the 11-item Iranian version of TSK-CF, where scores range from 11 to 44, with higher scores indicating greater fear. While the different versions of TSK-CF limit direct comparison, the findings still provide insight into intervention impacts on psychological fear of movement.

Due to the heterogeneity in interventions and outcome measurements, meaningful comparisons were challenging, precluding meta-analysis. The interpretation of individual study outcomes in relation to the review's key objectives — RTP timeframe and risk of reinjury — followed the inferential approach described in Section 3.2.3. This framing was used to guide the narrative synthesis presented below.

4.4 Review Findings

The findings from the six included studies (Ahmadi et al., 2020; Arundale et al., 2017; Bartels et al., 2016; Ghaderi et al., 2021; Gholami et al., 2023; Kasmi et al., 2023) are presented below, reported according to intervention for the primary outcomes of interest relating to RTP timeframe and incidence of reinjury.

Table 5. Results for studies reporting IKDC

Study	Method	Number of participants (n)	Pre-intervention IKDC score	Post-intervention IKDC score	p-values (P)	Effect size	Odds ratio
COMB program – plyometric and eccentric training combination							
Kasmi et al 2023	IKDC 2000				ANOVA p-value (Cohen's d) Time: 0.001 (4.61) Group: 0.001 (1.05) Group x Time: 0.001 (1.08)	?	?
ECC		10	43.30 ± 10.48	87.15 ± 3.67			
PLYO		10	43.40 ± 8.18	80.71 ± 2.89			
CONTROL		10	44.40 ± 9.28	71.39 ± 1.92			
COMB		10	43.90 ± 9.67	98.64 ± 1.42			
Neuromuscular training with external focus of attention							
Ghaderi et al 2021	Persian version of the IKDC Subjective Knee Evaluation Form (%)						?
Control Group		12	67.3 ± 8.1	68.8 ± 11.5	0.550	0.075	
Experimental group		12	65.6 ± 9.7	84.7 ± 1.8	0.003 (related to post hoc paired t-tests)	0.80	
SAP & PERT							
Arundale et al 2017	IKDC (no further specification) Normal Knee function		?	1 year follow-up (no. of subjects) 2 year follow-up No. of subjects)	ANOVA p-value p-value: 0.18 / 0.03 Group x Time: -3.7 (-8.6 to 1.3) / 3.9 (-0.8 to 8.5) P=0.03 1 year: Mean difference between SAP+PERT: 2.5 [-9.1 to 4.1] P=0.44 2 year: 5.0 [-1.5 to 11.5] P=0.13	?	0.31 (0.5-19.1) N//A
SAP Group		20		14/19			
SAP & PERT Group		20		18/20			
				17/17			
				1/19			

Abbreviations: ACL = Anterior Cruciate Ligament; RTP = Return to Play; RCT = Randomised Controlled Trial; NMT = Neuromuscular Training; SLH = Single-Leg Hop; SEBT = Star Excursion Balance Test; IKDC = International Knee Documentation Committee; KOOS = Knee Injury and Osteoarthritis Outcome Score; YBT = Y-Balance Test; TTS = Time to Stabilisation; EMG = Electromyography; VAS = Visual Analogue Scale.

Table 6. Results for studies reporting KOOS

Study	Method	Number of participants (n)	Pre-intervention KOOS score (Mean ± SD)	Post-intervention KOOS score (Mean ± SD)		p-values (P)			
COMB program – plyometric and eccentric training combination									
Kasmi et al 2023	The KOOS score for LCA injury					ANOVA p-value (Cohen's d)			
						Time	Group	Group x Time	
ECC PLYO CONTROL COMB		10 10 10 10	52.54 ± 4.36 52.04 ± 3.48 49.75 ± 2.52 52.40 ± 3.37	82.56 ± 1.22 81.23 ± 0.42 79.82 ± 1.52 93.26 ± 1.22		0.001 (9.48)	0.001 (1.69)	0.001 (1.39)	
SAP & PERT									
Arundale et al 2017	KOOS-Sports and Recreation		?	1 year follow-up (calculated as%)	2 year follow-up (calculated as %)	ANOVA p-value			
						p-value	Mean difference between 1 & 2 years	1 year Mean difference between SAP+PERT	2 year
SAP Group SAP & PERT		20 20		94% ± 8% 95% ± 9%	96% ± 12% 93% ± 13%	P=0.40	-1.8[-7.1 to 3.5] 1.3[3.7-6.3]	0.4[-6.1 to 5.4] P=0.90	2.7[-5.6 to 11.1] P=0.51
Arundale et al 2017	KOOS-quality-of-life scores		?	1 year follow-up (calculated as%)	2 year follow-up (calculated as %)	ANOVA p-value			
						p-value	Mean difference between 1 & 2 years	1 year Mean difference between SAP+PERT	2 year
SAP Group SAP & PERT		20 20		86% ± 11% 82% ± 18%	88% ± 13% 87% ± 16%	P=0.54	-1.8 (-8.5 to 4.8) -4.6 (-10.9 to 1.7)	3.4 [-7.0 to 13.9] P=0.51	0.7 [-9.3 to 10.6] P=0.89

Abbreviations: ACL = Anterior Cruciate Ligament; RTP = Return to Play; NMT = Neuromuscular Training; SLH = Single-Leg Hop; SEBT = Star Excursion Balance Test; IKDC = International Knee Documentation Committee; KOOS = Knee Injury and Osteoarthritis Outcome Score; YBT = Y-Balance Test; TTS = Time to Stabilisation; EMG = Electromyography; VAS = Visual Analogue Scale; ROM = Range of Motion; MVIC = Maximal Voluntary Isometric Contraction.

Table 7. Results for studies reporting Tampa kinesiophobia score (TSK-CF)

Study	Method	Number of participants (n)	Pre-intervention TSK-CF	Post-intervention TSK-CF	p-values (P)			Effect size
COMB program – plyometric and eccentric training combination								
Kasmi et al 2023	17 item TSK as described by ..				ANOVA p-value			?
					Time	Group	Group x Time	
ECC PLYO CONTROL COMB		10 10 10 10	50.00 ± 1.66 50.10 ± 1.73 48.40 ± 1.84 48.70 ± 2.00	35.60 ± 1.58 32.30 ± 1.25 41.10 ± 2.18 23.00 ± 1.05	0.001 (8.10)	0.001 (2.61)	0.001 (3.30)	
Differential learning and Visuomotor training								
Gholami et al 2023	Iranian Version of the TSK				ANOVA p-value			
					Time	Group	Group x Time	
DL VMT Control		15 15 15	37.6 ± 7.3 38 ± 6.7 37.4 ± 6.5	22.6 ± 4.8 ‡§ 23.3 ± 4.1 ‡§ 36.2 ± 6.0	F = 50.047 P<0.001*	F = 3.438 P = <0.029*	F = 6.154 P <0.001*	-2.42! (-3.76 to -1.09) -2.6! (-4.03 to -1.26) -0.19! (-1.20 to 0.82)

‡ = pretest to posttest significance difference
§ == significantly different from control group

*** = statistically significant difference (p<0.05)**

! = large Cohen's D effect size (0.8; Bonferroni Post Hoc test

Abbreviations: ACL = Anterior Cruciate Ligament; RTP = Return to Play; RCT = Randomised Controlled Trial; NMT = Neuromuscular Training; SLH = Single-Leg Hop; IKDC = International Knee Documentation Committee; KOOS = Knee Injury and Osteoarthritis Outcome Score; YBT = Y-Balance Test; TTS = Time to Stabilisation; EMG = Electromyography; VAS = Visual Analogue Scale; ROM = Range of Motion; MVIC = Maximal Voluntary Isometric Contraction; SEBT = Star Excursion Balance Test; SD = Standard Deviation; CI = Confidence Interval.

Table 8. Results for studies reporting Dynamic Balance and Postural Sway

Study	Method/Measurement Parameters						ANOVA					
External Focus of Attention & Continuous Cognitive Task												
Ahmadi et al 2020	Dependent Variables	Control condition		External Focus		Cognitive Focus		Main effect of:				Interaction between group and condition	
		ACL-R	Healthy	ACL-R	Healthy	ACL-R	Healthy	Condition		Group			
								P value	F ratio	P value	F ratio	P value	F ratio
	Area of 95% confidence ellipse (cm^2)	13.36 (3.27)	10.94 (4.59)	12.70 (4.25)	11.14 (3.88)	7.31 (2.26)	9.20 (4.07)	<0.01	18.87	0.43	0.62	<0.01	5.12
	SD of COP in AP (cm)	1.03 (0.17)	0.93 (0.22)	1.00 (0.25)	0.94 (0.22)	0.71 (0.13)	0.84 (0.24)	<0.01	16.07	0.86	0.03	0.01	4.91
	SD of COP in ML (cm)	0.69 (0.09)	0.62 (0.11)	0.68 (0.10)	0.63 (0.09)	0.54 (0.08)	0.57 (0.08)	<0.01	14.17	0.15	2.14	0.04	3.29
	Velocity of COP in AP (cm/s)	1.81 (0.40)	1.67 (0.34)	1.87 (0.48)	1.72 (0.35)	1.54 (0.45)	1.54 (0.33)	<0.01	10.02	0.37	0.80	0.35	1.02
	Velocity of COP in ML (cm/s)	2.46 (0.49)	2.21 (0.49)	2.42 (0.48)	2.23 (0.40)	2.19 (0.61)	2.09 (0.46)	<0.01	5.13	0.19	1.74	0.59	0.53
	MPF in AP (Hz)	0.257 (0.072)	0.263 (0.064)	0.263 (0.088)	0.248 (0.086)	0.326 (0.113)	0.271 (0.079)	0.02	3.96	0.26	1.30	0.18	1.70
	MPF in ML (Hz)	0.485 (0.130)	0.512 (0.132)	0.526 (0.123)	0.498 (0.103)	0.600 (0.186)	0.531 (0.127)	0.01	4.15	0.47	0.51	0.14	1.95
Differential learning and Visuomotor training													
Gholami et al 2023	Star Excursion Balance Test Variables (cm)	Pre-intervention		Post-intervention		Effect Size		P Value					
								Main effect of:				Group X Time interaction	
								Time		Group			
								P value	F ratio	P value	F ratio	P value	F ratio
DL VMT Control	Anterior	80.6 ± 3.9 80.4 ± 3.2 80.1 ± 3		89.5 ± 1.9 ‡ § 88.8 ± 1.4 ‡ § 81.5 ± 3.2		2.90 !(1.45 to 4.35) 3.40 !(1.81 to 4.98) 0.45(−0.57 to 1.47)		<0.001*	170.914	<0.001*	13.324	<0.001*	25.849

DL VMT Control	Anteromedial	81.8 ± 5 82.2 ± 4.8 82.5 ± 4.5	90.1 ± 3.4 ‡ § 89.8 ± 3.2 ‡ § 83.4 ± 3.9	1.94 !(0.71 to 3.16) 1.86 !(0.65 to 3.07) 0.21(−0.80 to 1.22)	<0.001*	48.253	<0.004*	6.221	<0.001*	9.617
DL VMT Control	Medial	81.8 ± 5 82.2 ± 4.8 82.5 ± 4.5	90.1 ± 3.4 ‡ 89.8 ± 3.2 ‡ 83.4 ± 3.9	1.94 !(0.71 to 3.16)1.86 !(0.65 to 3.07) 0.21(−0.80 to 1.22)	<0.001*	74.274	<0.039*	3.514	<0.001*	13.337
DL VMT Control	Posteromedial	78.7 ± 3.1 78.7 ± 3.1 78.7 ± 3.1	89 ± 4.4 ‡ § 87.8 ± 3.2 ‡ § 79.6 ± 2.9	2.70 !(1.30 to 4.10) 2.88 !(1.44 to 4.33) 0.30(−0.26 to 1.83)	<0.001*	162.347	<0.001*	12.205	<0.001*	31.295
DL VMT Control	Posterior	82.2 ± 3.3 81.9 ± 3.8 82.6 ± 3.7	90.1 ± 3.3 ‡ § 89.8 ± 3.3 ‡ § 83.2 ± 3.8	2.39 !(1.06 to 3.72) 2.22 !(0.93 to 3.50) 0.16(−0.85 to 1.17)	<0.001*	84.773	<0.009*	5.316	<0.013*	16.797
DL VMT Control	Posterolateral	76.4 ± 3.2 76.6 ± 3.3 76.9 ± 3.3	87 ± 4 ‡ § 85.9 ± 4 ‡ § 78 ± 1.8	2.92 !(1.47 to 4.38) 2.53 !(1.17 to 3.89) 0.41(−0.60 to 1.43)	<0.001*	147.187	<0.001*	10.384	<0.001*	26.928
DL VMT Control	Lateral	74.8 ± 4.6 74.3 ± 4.4 75 ± 4	87.6 ± 4.6 ‡ § 85.2 ± 3.7 ‡ § 76.1 ± 4.6	2.78 !(1.36 to 4.20) 2.68 !(1.28 to 4.07)0.25(−0.76 to 1.27)	<0.001*	123.620	<0.001*	9.974	<0.001*	23.937
DL VMT Control	Anterolateral	77 ± 4 78 ± 3.9 77.6 ± 4.3	88.6 ± 4 ‡ § 87.5 ± 4.1 ‡ § 78 ± 4.7	2.9 !(1.45 to 4.35) 2.37 !(1.05 to 3.69) 0.08(−0.92 to 1.10)	<0.001*	98.265	<0.001*	10.488	<0.013*	22.583

‡ = pretest to posttest significance difference

§ == significantly different from control group

*** = statistically significant difference (p<0.05)**

! = large Cohen's D effect size (0.8; Bonferroni Post Hoc test

Abbreviations: ACL = Anterior Cruciate Ligament; RTP = Return to Play; RCT = Randomised Controlled Trial; NMT = Neuromuscular Training; SLH = Single-Leg Hop; IKDC = International Knee Documentation Committee; KOOS = Knee Injury and Osteoarthritis Outcome Score; YBT = Y-Balance Test; SEBT = Star Excursion Balance Test; VAS = Visual Analogue Scale; ROM = Range of Motion; EMG = Electromyography; MVIC = Maximal Voluntary Isometric Contraction; TTS = Time to Stabilisation; SD = Standard Deviation; CI = Confidence Interval; NR = Not Reported.

Table 9. Results for studies reporting biomechanics (kinematic and kinetic data)

Study	Method	Pre-intervention	Post-intervention	Effect Size	p-values (P)
External focus of attention					
Ghaderi et al 2021	Kinematics				Between group differences (ANCOVA)
	Peak trunk flexion (degrees)				
Control Group Experimental Group		27.2 ± 10.8 23.2 ± 10.3	28.3 ± 10.7 48.3 ± 10.8	0.050 0.76	0.003*
Control group Experimental group	Peak hip flexion (degrees)	38.6 ± 10.9 22.3 ± 6.8	37.9 ± 12.5 35.3 ± 5.1	0.205 0.73	0.008*
Control group Experimental group	Peak knee flexion (degrees)	23.5 ± 9.1 39.7 ± 12.54	27.3 ± 9.2 56.8 ± 10.3	0.030 0.60	0.012*
Control group Experimental group	Peak Knee Abduction (degrees)	7.8 ± 1.1 8.1 ± 1.18	7.6 ± 0.9 5.7 ± 0.8	0.101 0.77	0.018*
Control group Experimental group	Peak Knee Internal Rotation (degrees)	14.4 ± 1.7 15.9 ± 2.15	14.5 ± 1.9 12.8 ± 1.2	0.001 0.76	0.022*
	Kinetics				0.008*
Control group Experimental group	Peak Reaction Force, (N/BW)	3.9 ± 1.2 3.4 ± 1.19	3.8 ± 1.1 2.2 ± 0.5	0.030 0.54	
Control group Experimental group	Peak Anterior Tibial shear force (BW)	0.8 ± 0.5 0.8 ± 0.6	0.8 ± 0.7 0.7 ± 0.5	0.027 0.66	0.018*
Control group Experimental group	Peak knee extension moment (Nm/kg)	3.8 ± 1.1 3.5 ± 1.3	3.9 ± 0.8 2.7 ± 0.7	0.029 0.59	0.022*
Control group Experimental group	Peak Knee abduction Moment (Nm/kg)	1.5 ± 1.2 1.6 ± 0.7	1.6 ± 1.1 1.0 ± 0.8	0.032 0.64	0.014*
Control group Experimental group	Loading rate (BW/S)	45.4 ± 10.7 47.6 ± 6.9	46.9 ± 8.1 34.1 ± 8.5	0.022 0.81	0.016*
Control group Experimental group	Position Sense Errors (degrees)	6.7 ± 3.7 5.8 ± 1.67	6.5 ± 2.9 2.8 ± 1.1	0.030 0.73	0.001*

Differential learning and Visuomotor training							
Gholami et al 2023	Kinematics				ANOVA p-value		
					Time	Group	Group x Time
DL VMT Control	Hip flexion (degrees)	55.9 ± 5.5 50.5 ± 7.7 51.9 ± 11	62 ± 6.1 ‡§ 56.6 ± 7.8 ‡§ 51.8 ± 11	1.05! (-0.29 to 2.13) 0.78 (-0.26 to 1.83) -0.00 (-1.02 to 1)	F = 31.011 P<0.001*	F = 2.979 P = <0.062*	F = 8.386 P <0.001*
DL VMT Control	Knee flexion (degrees)	28.1 ± 7.1 27.8 ± 5.9 26.6 ± 4.8	39.2 ± 4.5 ‡§ 41.7 ± 3.07 ‡§ 25.9 ±	1.86! (0.65 to 3.08) 2.95! (1.49 to 4.42) -0.12 (-1.21 to 0.81)	F = 55.063 P<0.001*	F = 20.632 P<0.001*	F = 18.190 P<0.001*
DL VMT Control	Ankle Dorsiflexion (degrees)	18.2 ± 1.8 19.7 ± 1.2 21.9 ± 2.2	23 ± 3.6 ‡ 25.7 ± 4.3 ‡ 22.1± 2.2	1.68 (-0.50 to 2.86) 1.90 (0.68 to 3.12) 0.09 (-0.61 to 1.43)	F = 53.829 P<0.001*	F = 4.095 P<0.024*	F = 8.469 P<0.001*
DL VMT Control	Knee Valgus (degrees)	-4.9 ± 0.2 -5.3 ± 0.4 -5.1 ± 0.4	-3.6 ± 0.2 ‡§ -3.8 ± 0.3 ‡§ -5.2 ± 0.4	6.5! (3.96 to 9.03) 4.24! (2.41 to 6.06) -0.12 (-1.26 to 0.76)	F = 119.261 P<0.001*	F = 53.577 P<0.001*	F = 39.136 P<0.001*
	Kinetics						
DL VMT Control	Vertical Ground Reaction Force (N)	3.3 ± 0.2 3 ± 0.4 3.4 ± 0.4	2.8 ± 0.1 ‡§ 2.7 ± 0.1 ‡§ 3.3 ± 0.5	-3.16! (-4.68 to -1.64) -1.02! (-2.10 to 0.04) -0.22 (-1.52 to 0.52)	F = 51.717 P<0.001*	F = 8.211 P<0.001*	F = 4.870 P<0.013*

‡ = pretest to posttest significance difference
§ == significantly different from control group

*** = statistically significant difference (p<0.05)**

! = large Cohen's D effect size (0.8; Bonferroni Post Hoc test)

Abbreviations: ACL = Anterior Cruciate Ligament; RTP = Return to Play; RCT = Randomised Controlled Trial; NMT = Neuromuscular Training; SLH = Single-Leg Hop; SEBT = Star Excursion Balance Test; IKDC = International Knee Documentation Committee; KOOS = Knee Injury and Osteoarthritis Outcome Score; YBT = Y-Balance Test; VAS = Visual Analogue Scale; ROM = Range of Motion; EMG = Electromyography; MVIC = Maximal Voluntary Isometric Contraction; TTS = Time to Stabilisation; SD = Standard Deviation; CI = Confidence Interval; NR = Not Reported; ↑ = Increase; ↓ = Decrease.

Table 10. Results for studies reporting various functional measures

Study	Method	Number of participants (n)	Pre-intervention	Post-intervention	p-values (P)						Effect size
SpeedCourt System											
Bartels et al 2016	Functional measure				ANOVA p-value (Cohen's d)						?
					Time		Group		Group x Time		
					p	n^2	p	n^2	p	n^2	
SpeedCourt Control	Jump Height unilateral operated leg (cm)	22 14	11.0 ± 5.3 12.2 ± 2.9	13.8 ± 5.2 13.4 ± 4.0	**<0.001**	**0.530**	0.792	0.002	**0.020**	**0.148**	
SpeedCourt Control	Ground Contact Time operated leg(s)	22 14	0.33 ± 0.08 0.37 ± 0.09	0.29 ± 0.09 0.33 ± 0.08	**<0.001**	**0.488**	0.195	0.049	0.919	<0.001	
SpeedCourt Control	Reaction Time operated leg (s)	22 14	1.38 ± 0.33 1.38 ± 0.11	1.26 ± 0.31 1.33 ± 0.08	**<0.001**	**0.392**	0.673	0.005	**0.025**	**0.138**	
SpeedCourt Control	Knee Joint Extension operated leg (°)	24 14	1.0 ± 1.6 0 ± 0	0.3 ± 1.1 0 ± 0	0.245	0.037	**0.007**	**0.185**	0.245	0.037	

SpeedCourt Control	Knee Joint Flexion operated leg (°)	24 14	124.00 ± 8.0 126.1 ± 5.8	127.5 ± 8.9 127.9 ± 6.7	**0.003**	**0.220**	0.743	0.003	0.493	0.013	
Differential learning and Visuomotor training											
Gholami et al 2023	Triple Hop Test (cm)				P Value						
					Time		Group		Group x Time		
DL VMT Control		15 15 15	457.3 ± 51.2 456.4 ± 54 455.6 ± 51	531.3 ± 74.4 ‡§ 517.6 ± 78.9 ‡ 457.4 ± 51.1	F = 16.226 P<0.001*		F = 2.609 P = <0.085		F = 3.861 P <0.029*		1.15! (0.06 to 2.25) 0.90! (-0.15 to 1.96) 0.03 (-0.97 to 1.04)
SAP & PERT											
Arundale et al 2017	Functional Measure	Participants (n)	1 year follow-up	2 year follow-up	P value				Time x Group Interaction (p)		Effect Size	
					1 year		2 year				1 year	2 years
SAP SAP & PERT	Quadriceps Strength Limb Symmetry	20 20	101 ± 14 101 ± 14	103 ± 11 98 ± 14	0.93		0.31		0.45		0.4 (-9.0 to 9.8)	4.5 (-4.3 to 13.1)
SAP SAP & PERT	Single leg hop for distance limb symmetry	20 20	99 ± 9 98 ± 6	99 ± 6 100 ± 6	0.57		0.71		0.31		1.4 (-3.5 to 6.2)	0.8 (-5.4 to 3.7)
SAP SAP & PERT	Crossover hop for distance limb symmetry	20 20	103 ± 9 99 ± 6	103 ± 9 99 ± 4	0.16		0.07		0.81		4.0 (-1.6 to 9.8)	4.6 (-0.3 to 9.6)

SAP SAP & PERT	Triple hop for distance limb symmetry	20 20	100 ± 7 97 ± 7	102 ± 6 99 ± 5	0.19	0.33	0.65	3.1 (-1.6 to 7.8)	2.1 (-2.1 to 6.3)
SAP SAP & PERT	Six-meter timed hop limb symmetry	20 20	103 ± 7 103 ± 6	100 ± 6 100 ± 7	0.92	0.97	0.91	0.2 (-4.8 to 5.3)	0.1 (-4.8 to 4.6)

COMB program – plyometric and eccentric training combination									
Kasmi et al 2023	Ratio Peak Torque and Total Work		Ratio		Delta%		Effect Size		ANOVA p-value (Cohen's d)	
			PT	TW	PT	TW	PT	TW	PT	TW
			Angular velocity of 90 °/s							
		CON (n=10) ECC (n=10) PLYO (n=10) COMB (n=10)	81.73±12.57 43.52±4.54 94.10±6.38 56.50±2.67	86.18±9.13 48.48±4.01 97.25±9.81 59.81±2.54	-29.5 32.3 -39.8 -4.50	-29.00 24.4 -38.8 -3.4	1.92 3.10 5.88 0.94	2.74 2.94 3.85 0.80	0.001 (0.09)	0.001 (0.4)
			Angular velocity of 180 °/s							
		CON (n=10) ECC (n=10) PLYO (n=10) COMB (n=10)	83.85±10.54 45.21±2.51 97.47±5.66 56.56±2.17	86.36±7.30 45.97±2.6 97.80±8.85 59.81±2.43	-31.4 29.9 -40.3 -3.40	-28.3 33.1 -37.6 -2.80	2.49 5.40 6.93 0.89	3.35 5.71 4.16 0.70	0.001 (0.03)	0.001 (0.15)
			Angular velocity of 240 °/s							
		CON (n=10) ECC (n=10) PLYO (n=10) COMB (n=10)	79.12±3.34 45.10±2.07 98.67±6.34 57.01±2.37	83.17±4.76 45.47±4.10 100.76±6.46 59.94±2.00	-26.5 29.7 -40.5 -4.6	-25.9 30.6 -39.3 -3.30	6.29 6.47 6.32 1.10	4.53 3.39 6.13 0.98	0.001 (0.05)	0.001 (0.17)
	Limb Symmetry Index Peak Torque and Total Work		Extensors				Flexors			
			LSI-PT(Nm/kg)		LSI-TW(J)		LSI-PT(Nm/kg)		LSI-TW(J)	
			All ANOVA p-value's = 0.001							
			Angular velocity of 90 °/s							
		CON (n=10) ECC (n=10) PLYO (n=10) COMB (n=10)	67.40±9.54 117.20±18.89 69.40±4.70 98.70±0.82		70.60±10.06 115.40±16.53 72.00±6.80 98.40±0.70		77.10±6.03 82.10±12.29 105.80±6.46 102.30±2.87		77.30±6.72 84.10±12.39 106.80±5.01 101.40±2.22	
			Angular velocity of 180 °/s							

		CON (n=10) ECC (n=10) PLYO (n=10) COMB (n=10)	68.60±6.06 110.80±13.30 70.60±5.30 98.30±0.82	71.30±8.30 114.20±14.46 72.30±4.92 98.50±0.85	78.40±4.74 78.60±10.59 105.70±7.69 102.70±2.79	79.40±5.42 79.70±12.29 106.20±5.22 102.50±2.42
			Angular velocity of 240 °/s			
		CON (n=10) ECC (n=10) PLYO (n=10) COMB (n=10)	68.60±6.93 112.50±13.63 71.90±5.04 98.40±0.84	71.30±7.83 114.20±14.77 73.50±4.33 98.60±0.84	79.70±4.32 83.60±13.33 106.10±6.23 103.00±3.30	79.20±5.63 83.40±14.37 107.70±6.17 103.10±3.48

‡ = pretest to posttest significance difference
§ == significantly different from control group

*** = statistically significant difference (p<0.05)**

! = large Cohen's D effect size (0.8; Bonferroni Post Hoc test

Abbreviations: ACL = Anterior Cruciate Ligament; RTP = Return to Play; RCT = Randomised Controlled Trial; NMT = Neuromuscular Training; SLH = Single-Leg Hop; SEBT = Star Excursion Balance Test; IKDC = International Knee Documentation Committee; KOOS = Knee Injury and Osteoarthritis Outcome Score; YBT = Y-Balance Test; VAS = Visual Analogue Scale; ROM = Range of Motion; EMG = Electromyography; MVIC = Maximal Voluntary Isometric Contraction; TTS = Time to Stabilisation; SD = Standard Deviation; CI = Confidence Interval; NR = Not Reported; ↑ = Increase; ↓ = Decrease; ns = Not Significant.

4.4.1 External Focus of Attention

Two studies (n=64) explored the impact of an EF during exercise on four key outcomes. The first study by Ahmadi et al.,(2020) (n=40), an analytical cross-sectional study, found no significant differences in postural control between exercises performed with an EF and those in the control condition ($P < 0.05$). The second study, a randomized clinical trial by Ghaderi et al.,(2021) (n=24), reported significant post-intervention improvements in several biomechanical markers, knee joint position sense, and patient-reported function (IKDC scores). Participants in the intervention group (n=12) demonstrated decreased loading rates (34.1 ± 8.5) and peak anterior tibial shear force (0.7 ± 0.5) alongside increased trunk (48.3 ± 10.8), hip (35.3 ± 5.1), and knee flexion (56.8 ± 10.3) angles, with reductions in knee abduction (5.7 ± 0.8) and internal rotation (12.8 ± 1.2) compared to the control group.

Improved landing biomechanics were indicated by reductions in landing forces, vertical ground reaction force (vGRF) (2.2 ± 0.5), knee extension (2.7 ± 0.7), and knee abduction moments (1.0 ± 0.8). Position sense errors improved by 51% (from 5.8 at baseline to 2.8 at follow-up). Effect sizes for these biomechanical markers were greater than 0.5 in the intervention group and less than 0.3 in the control group. Collectively, these findings suggest that while neuromuscular training with EF cueing may not affect dynamic postural control, it significantly improves biomechanics, potentially reducing the risk of secondary ACL injuries.

4.4.2 Continuous Cognitive Task

A single study by Ahmadi et al.,(2020) (n=40) examined the impact of a CCT on postural control in a cohort of ACLR patients and a control group of healthy individuals. In this study, Gholami et al.,(2023) used the SEBT to measure balance displacement in centimetres, while Ahmadi et al.,(2020) evaluated static balance and dynamic postural sway using multiple variables: the standard deviation of the centre of pressure (COP), COP velocity, and mean power frequency (MPF) in both anterior-posterior (AP) and mediolateral (ML) directions.

Among the ACLR group (n=20), participants exhibited reduced sway area (7.31 ± 2.26) and lower standard deviations of COP (0.71 ± 0.13 in the AP direction; 0.54 ± 0.08 in the ML direction) during CCT compared to the EF and control conditions. The

effect of CCT on postural sway was notably greater in the ACLR group than in healthy participants (n=20), likely due to the ACLR group's existing deficits in automatic postural control. In contrast, the conditions tested had minimal effect on the postural stability of healthy participants. Thus, CCT appears more beneficial than EF for enhancing static standing balance and dynamic postural sway in ACLR athletes.

4.4.3 Differential and Visuomotor Training

A study by Gholami et al.,(2023) (n=45) examined the effects of DL compared to VMT on functional performance, dynamic balance as measured by the SEBT, biomechanics during a single-leg drop jump, and kinesiophobia in patients post-ACLR. The DL group demonstrated higher performance improvements across most measures compared to the VMT group. Both DL (effect size = 1.15 [0.06 to 2.25]) and VMT (effect size = 0.90 [-0.15 to 1.96]) groups showed significant gains from pre- to post-test in the triple-hop test, with the DL group performing significantly better than the control group (0.03 [-0.97 to 1.04]).

In terms of functional biomechanics, athletes from both intervention groups, prior to the intervention, showed extended knee positions, increased hip flexion, and anterior pelvic tilt upon landing on the involved limb, potentially compensating for reduced knee work during the triple-hop test. The biomechanical analysis revealed that, post-intervention, both DL and VMT groups exhibited increased hip and knee flexion, ankle dorsiflexion, decreased knee valgus, and reduced vGRF. This shift towards increased stiffness in the lower extremities may reduce hazardous joint positions associated with ACL injury risk and contributed to improvements in triple-hop test performance.

Regarding dynamic balance, both DL and VMT groups showed significant improvements in all SEBT directions, with a significant advantage over the control group across all but the medial direction. The notable effect sizes indicate that DL led to greater improvements than VMT in most directions (except anterior and posteromedial), supporting both programs' effectiveness in enhancing neuromuscular control following ACLR.

For kinesiophobia, both DL and VMT groups had statistically significant reductions in Tampa Scale of Kinesiophobia (TSK) scores from pre- to post-test (DL from 37.6 ± 7.3 to 22.6 ± 4.8; VMT from 38 ± 6.7 to 23.3 ± 4.1), significantly more than the control group (P = <0.029). This reduction suggests a positive psychological impact of both intervention types.

In summary, both DL and VMT, with their enhanced motor variation training, led to greater recovery improvements than traditional rehabilitation routines. While both interventions were effective, DL demonstrated higher effect sizes across most outcomes, supporting it as a potentially superior approach. This study highlights that DL and VMT training can positively influence performance, biomechanics, and psychological recovery, offering promising alternatives that can be incorporated during and after conventional ACL rehabilitation to address second injury risk factors.

4.4.4 Combination of Eccentric and Plyometric intervention

In a study by Kasmi et al., 2023) (n=40), participants in the COMB group, which included both plyometric and eccentric training, showed notable improvements in isokinetic strength, psychological well-being, and functional self-reported outcomes following intervention. The COMB group exhibited substantial score increases across KOOS (pre = 52.40 ± 3.37; post = 93.26 ± 1.22), IKDC (pre = 43.90 ± 9.67; post = 98.64 ± 1.42), and TSK-CF (pre = 48.70 ± 2.00; post = 23.00 ± 1.05) compared to groups that underwent only eccentric (ECC), plyometric (PLYO), or control (CON) programs. These results suggest that the COMB group benefited from a comprehensive training approach that not only imposed greater physical demands but also enhanced psychological resilience, likely through improved confidence levels in athletic performance.

The COMB group’s gains in muscle strength performance were the most pronounced, supporting its effectiveness in stimulating adaptive muscle morphology in post-ACLR athletes. These findings indicate that combining plyometric and

eccentric training yields greater improvements in isokinetic strength and psychological health than single-mode interventions, making it an effective strategy to facilitate a safe and confident return to sports after ACLR.

4.4.5 SpeedCourt training:

Bartels et al.,(2016) (n=50) observed significant improvements in jump height (from 11.0 ± 5.3 to 13.8 ± 5.2) and reaction time (from 1.38 ± 0.33 to 1.26 ± 0.31) in the SpeedCourt training group (n=22) after six high-reactive therapy sessions compared to a sensomotoric therapy intervention group (n=14). Additionally, the SpeedCourt group showed notable reductions in the discrepancies between the operated and non-operated leg regarding tapping, jump height, and ground reaction time parameters. Although a significant enhancement in lower leg anthropometric dimensions was also reported, these measurements were not considered outcomes in this review.

4.4.6 Perturbation Training

An RCT by Arundale et al.,(2017) (n=40) assessed the impact of added perturbation training on quadriceps strength and single-legged hop test performance following ACLR, finding no significant improvements. Both the standard ACL-SPORTS program (SAP) group and the SAP with added perturbation (SAP+PERT) group showed similar mean limb symmetry scores (95% at each assessment) for both quadriceps strength and single-legged hop testing. There were also no clinically meaningful differences between groups in IKDC, KOOS-sports and recreation, or KOOS-quality-of-life scores, nor in time from surgery to passing RTP criteria. Based on minimum clinically important difference (MCID) scores for the IKDC and KOOS, these findings suggest that the addition of perturbation training does not meaningfully impact patient-reported functional outcomes at 1 and 2 years post-ACLR.

Notably, at the 2-year mark, a smaller proportion of athletes in the SAP+PERT group reported normal knee function on the IKDC, though this outcome was not considered due to timeframe limitations outlined in the study’s inclusion criteria. Interestingly, four

of five athletes in the SAP+PERT group showed a decrease in IKDC scores between years 1 and 2 (greater than the MCID) despite improvements in objective measures like quadriceps strength and single-legged hop symmetry. Closer analysis of changes during this period is warranted, as no clear pattern emerged to explain this decline.

There were also no significant differences between groups in the time taken to meet RTP criteria, suggesting that perturbation training may not expedite readiness for sports. Across both groups, the average time to pass these criteria ranged from 8 to 11 months post-surgery. While the study found no added benefit from perturbation training, it emphasizes the need for further research to examine the roles of rehabilitation timelines, treatment protocols, and specific RTP criteria in minimizing reinjury risk.

4.5 Summary

Given the results of this study, the objectives were partially met. The study aimed to:

- Compare the effectiveness of neuroplasticity and motor learning-based therapeutic interventions against traditional rehabilitation methods in athletes post-ACLR.

The results indicate that interventions such as Differential Learning (DL), Visuo-Motor Training (VMT), and combination programs (plyometric and eccentric training) demonstrated superior outcomes in terms of functional performance, psychological well-being, and dynamic balance compared to traditional methods. These findings support the effectiveness of neuroplasticity and motor learning-based interventions. However, results from interventions like perturbation training and SpeedCourt training showed limited or inconclusive benefits compared to traditional methods, indicating variability in the success of neuroplasticity-based approaches.

- Investigate the relationship between neuroplasticity, motor learning, RTP timelines, and re-injury rates in this population.

While the studies explored RTP timelines and functional improvements, there was limited direct evidence linking these outcomes to reduced re-injury rates. The inclusion of measures such as limb symmetry indices, psychological assessments, and biomechanics indirectly highlights factors influencing re-injury risks. However, the lack of long-term follow-up data or explicit reporting on re-injury rates limits the ability to comprehensively address this objective.

In conclusion, while the study provides robust evidence supporting the benefits of specific neuroplasticity and motor learning-based interventions, further research is required to clarify their impact on re-injury rates and refine their application to optimize RTP outcomes in ACLR athletes.

Table 11. Summary of individual study findings with regards to the overall effectiveness of the interventions on the study outcomes

Citation	IKDC		KOOS	TSK-CF	Dynamic Balance & Postural Sway	Biomechanics	Functional measures
	External focus of attention & Continuous Cognitive Task						
Ahmadi et al 2020 Control Group CCT Group EF Group					 O Y O		
Ghaderi et al 2021 Control Group Experimental Group	 O Y					 O Y	
	SpeedCourt System						
Bartels et al 2016 Control Group Intervention Group							 Y(-) Y
	Combined Eccentric and Plyometric Training						
Kasmi et al 2023 ECC PLYO COMB CON	 Y+++ Y++ Y+ Y		 Y+ Y Y+++ Y++	 Y+ Y++ Y+++ Y			 Y
	Differential Learning and Visuomotor Training						
Gholami et al 2023 DL VMT Control				 Y Y O	 Y Y O	 Y Y O	 Y Y O
	SAP & PERT						

Arundale et al 2017 SAP group SAP & PERT	 O N		 O O				 O O

Y = Improved

(-) = Improvement but not statistically significant

(+) = degree of improvement in comparison to other groups

O = unchanged

N = worse

? = data unclear

‡ = data not presented

Chapter 5 Discussion

This review aimed to evaluate the impact of neuroplastic interventions on accelerating the return-to-play (RTP) timeframe and lowering the risk of reinjury after anterior cruciate ligament reconstruction (ACLR). A significant challenge was the limited number of clinical trials focused specifically on neuroplastic treatments for athletes post-ACLR. Most existing studies primarily address improvements in day-to-day function for ACLR patients rather than sport-specific RTP outcomes. However, despite the limited evidence, findings from this review suggest that neuroplastic-focused interventions could effectively shorten the RTP timeline, although additional research is needed to clarify their effect on reinjury prevention.

5.1 Time from ACLR to RTP

To date, no studies have specifically used the time from ACLR to RTP as a direct outcome measure for evaluating intervention effectiveness. Bartels et al. (2016) argue that the RTP timeframe alone should not be the sole criterion for determining an athlete's readiness to resume specific sports activities. Currently, clinical trials evaluating intervention efficacy often rely on outcome measures tied to traditional RTP tests. While this review used these conventional outcomes to assess effectiveness, the findings—interpreted through inference and application—suggest that these interventions may be associated with an accelerated RTP timeline. However, the evidence does not yet demonstrate a clear relationship between these interventions and reduced reinjury incidence, highlighting the need for further research that investigates this association more directly.

Machan and Krupps (2021) observed that traditional RTP tests are insufficient for identifying patients at risk of secondary injuries post-RTP, a limitation Grooms et al. (2023) attribute to these tests' narrow scope. While conventional assessments effectively reveal musculoskeletal impairments, they fail to account for neurocognitive reliance in motor tasks—an essential factor in reinjury risk. Exploring whether motor learning interventions reduce reinjury risk would require outcome measures that

incorporate neurocognitive components. However, as no current studies employ such measures, this review cannot definitively describe the nature or strength of the relationship between these interventions and reinjury risk following RTP.

5.2 Outcome measures

The outcome measures employed in studies included in this review are standard tools utilized by clinicians to evaluate an athlete's readiness for RTP. These assessments encompass a range of factors, including functional and biomechanical parameters, static balance and postural sway, kinesiophobia, psychological readiness, and patient-reported outcomes. Despite the variability in assessment and intervention methods across the included studies, the primary finding of this review indicates that most neuroplastic interventions yielded statistically significant improvements in the measured outcomes when compared to traditional intervention approaches.

Two studies, conducted by Ahmadi et al.,(2020) and Ghaderi et al.,(2021), investigated the effects of employing an external focus of attention (EF) during rehabilitation. Due to the heterogeneity in their study designs, direct comparisons of the intervention's effects are challenging; however, both studies concluded that this approach did not yield specific improvements in dynamic postural control. Although EF did not significantly influence this particular outcome, the incorporation of continuous cognitive tasks (CCT), differential learning (DL), or visuo-motor training (VMT) into rehabilitation programs appears to be more effective in enhancing postural sway and dynamic balance.

Ahmadi et al.,(2020) specifically found that following ACLR patients exhibited greater improvements in postural sway after the introduction of CCT compared to healthy individuals. This difference is likely attributed to the automatic control of movement that healthy patients already possess, which may limit their ability to benefit from such interventions to the same extent as those recovering from injury. The authors acknowledged uncertainty regarding what participants in the control condition focused on, which may reduce the reliability of the study’s results despite its high

critical appraisal rating. This lack of control over participants' focus introduces a potential confounding factor, as it remains unclear whether the observed effects were solely attributable to the intervention or were influenced by varying attentional focus among control participants.

A scoping review by Dheming et al.,(2023) identified four main areas where neurocognitive rehabilitation could have significant impact: postural control, proprioception, cognitive tasks, and visual tasks. Notably, this review included findings from Ahmadi et al.,(2020) which contrasted with those of Mohammadi et al., (2016) (date) that examined postural stability using the Biodex® Balance System alongside a cognitive task in which participants identified pitches and sounds. Ahmadi et al.,(2020) reported that CCT's improved postural control, while Mohammadi et al., (2016)found that post-ACLR, cognitive performance declined with no observed improvement in postural control. Supporting these mixed findings, three other studies in the review showed that either postural control or cognitive function tended to be compromised when post-ACLR participants engaged in simultaneous cognitive challenges.

Using EF, DL and VMT in addition to traditional interventions compared to traditional interventions alone, led to an improvement in various biomechanical markers, functional performance parameters and patient-reported function. Although the study by Ghaderi et al.,(2021) received a high critical appraisal rating, indicating reliable results, the authors noted a limitation in their choice of comparator group. Instead of using exercises with an internal focus of attention, the comparator group followed a standard neuromuscular training program. This design choice made it difficult to ascertain whether the observed changes in participants were due to the neuromuscular training itself or specifically to the emphasis on EF instructions.

While Gholami et al. (2023) found DL to have the largest effect sizes, VMT has also been validated as an effective alternative for managing neuroplastic changes in the central nervous system (CNS). In a randomized controlled trial (RCT) conducted by Bodkin et al. (2021), a single session of VMT successfully countered negative

neuroplastic adaptations by significantly increasing corticospinal excitability in the quadriceps muscle of ACLR patients, compared to one session of passive knee motion—a method previously used to modulate corticospinal excitability. This suggests VMT's potential as a proactive approach to enhancing neuroplastic recovery post-ACLR.

Notably, the study by Gholami et al. (2023) was conducted in a controlled laboratory environment, which may have enhanced internal validity by reducing external variability. However, such settings differ significantly from real-world rehabilitation environments, and this may limit the generalisability of the findings. In contrast, other included studies were carried out in clinical or sport-specific contexts, potentially providing more ecologically valid insights into patient performance and neurocognitive demands during rehabilitation.

DL has been shown to significantly enhance performance in the triple hop test, with notable improvements in key biomechanical parameters compared to control athletes. Participants in the DL group exhibited increased hip and knee flexion, improved ankle dorsiflexion, decreased knee valgus, and reduced vertical ground reaction forces (VGRF). The greater improvements in triple-hop test scores observed in this group can likely be attributed to the variability in training, which fosters subconscious knowledge and experience in managing deviations from expected performance.

5.3 Biomechanical adaptations

Regarding functional performance, biomechanical assessments revealed that athletes from both intervention groups tended to land on the involved limb with a more extended knee position, accompanied by increased hip flexion and anterior pelvic tilt prior to the intervention. This positioning across the entire kinetic chain appears to serve as a compensatory mechanism for the reduced knee work observed during all phases of the triple-hop task. Biomechanical analyses indicated alterations in lower extremity mechanics, and it is generally accepted that reduced hip, ankle, and knee flexion, along with increased knee valgus, heightens the risk of ACL injury.

The observed increases in these angles following the interventions suggest improved joint stiffness, potentially reducing the previously hazardous positions that contribute to injury risk. These biomechanical adjustments may have played a role in the enhancements noted in the triple-hop test, suggesting that such interventions could significantly mitigate risk factors associated with secondary ACL injuries.
However, it is important to recognize that the findings from Gholami et al.,(2023) may not be universally applicable across all sports, as participants were exclusively selected from handball, volleyball, and basketball backgrounds. While the study yielded reliable results, the authors acknowledged that including additional biomechanical parameters could have enriched the dataset and further substantiated the effectiveness of the interventions. This limitation suggests a need for caution when extrapolating results to broader athletic populations and highlights the importance of tailored interventions based on specific sports and individual needs.

An RCT by Ghanati et al.,(2022) found similar results, although their study focused on reducing biomechanical risk factors to prevent primary ACL injuries. Both DL and EF methods demonstrated positive effects in minimizing potential kinetic and kinematic risk factors associated with ACL injury. The DL method stood out for its effectiveness due to its emphasis on variability in training. Tailoring training conditions through varied movement patterns, rather than repeating the same movements, appears to be especially beneficial.

5.4 Kinesiophobia

DL, VMT and COMB training have been shown to effectively improve kinesiophobia, as demonstrated in studies by An & Swanik (2016) and Dudley et al.,(2022). Kinesiophobia, characterized as a fear of movement, is a significant factor contributing to altered biomechanics following ACLR. This fear often manifests unconsciously as a protective mechanism aimed at preventing further injury.

However, kinesiophobia can have detrimental effects on athletes' rehabilitation and performance outcomes. Research indicates that it is a key factor behind the inability of athletes to return to their preinjury levels of performance. Specifically, kinesiophobia negatively impacts self-reported functional abilities, hopping performance, self-reported levels of physical activity, and quadriceps strength, as highlighted by Dudley et al.,(2022). Addressing kinesiophobia through targeted interventions is crucial for facilitating a successful RTP and ensuring that athletes regain their confidence in their physical abilities. By incorporating strategies such as DL, VMT, and COMB training, rehabilitation programs can help reduce the fear of movement, thereby promoting better functional outcomes and enhancing overall recovery following ACLR. These findings underscore the importance of a comprehensive rehabilitation approach that not only focuses on physical recovery but also addresses psychological factors influencing athletes' readiness to return to sport.

The interplay between cognitive processing, emotional regulation, and motor control is crucial for understanding the rehabilitation challenges faced by athletes after ACLR. The frontal areas of the brain, responsible for cognitive processing related to motor control, also play a significant role in emotional regulation. Fear, a potent emotion, can lead to increased neural activity in the frontal lobe, which subsequently projects vital information to other brain regions involved in sensorimotor control. This heightened activity can disrupt the neurocognitive strategies necessary for maintaining knee stiffness and stability during movement, as noted by An & Swanik (2016).

Research by Trigsted and Bell (2017) further supports this notion, revealing that an increase in kinesiophobia is directly linked to heightened muscle activation prior to landing in a drop jump. This response may help explain the stiffening strategies often observed in patients who have undergone ACLR, as they compensate for perceived instability or risk of reinjury (Dudley et al., 2022).

The biomechanical and functional performance improvements seen EF, DL, and VMT may, in part, be attributed to a reduction in kinesiophobia. Dudley et al., (2022) propose that employing an EF can effectively divert a patient's attention away from their fears and towards an external object or goal. This shift in focus is associated with increased knee flexion, enhanced landing strategies, and optimized motor performance, thereby facilitating a more effective rehabilitation process.

Incorporating these psychological insights into rehabilitation programs not only addresses the physical aspects of recovery but also helps mitigate the psychological barriers posed by kinesiophobia. By fostering a more confident mindset and reducing fear-related responses, athletes may experience improved functional outcomes and a smoother transition back to sport following ACLR.

5.5 Combination of plyometric, eccentric and concentric training (COMB approach)

The COMB training approach has demonstrated superior improvements in measures of isokinetic strength compared to traditional single-mode interventions, such as plyometrics, concentric, and eccentric training. According to Kasmi et al.,(2023), plyometric exercises enhance eccentric force production in the lower body more effectively than traditional strength training. This enhancement is attributed to several mechanisms, including increased peripheral and central neural activity, recruitment of alpha motor neurons, heightened brain activation, increased corticospinal excitability, and improved sarcolemma activity. These neurophysiological adaptations resulting from COMB training appear to facilitate a more effective RTP participation following ACLR.

However, the findings of this study are somewhat limited in their generalizability due to the narrow age range and level of participation of the participants. This limitation raises concerns about whether the results can be applied to broader age groups or different athletic populations. Furthermore, potential bias could be introduced by the familiarization session conducted one week prior to the study. This session may have

influenced participants' performance and comfort levels with the testing protocols, thereby affecting the outcomes.

As a result, while improvements associated with COMB training are promising, the reliability and broader applicability of these findings must be considered cautiously. Future research should aim to include a more diverse participant pool and consider the impact of familiarization sessions on performance metrics to better ascertain the effectiveness of various training interventions in enhancing recovery and performance post-ACLR.

5.6 The SpeedCourt Device

The SpeedCourt device introduces an innovative approach to rehabilitation by enabling athletes to train with unexpected disturbance programs that target rapid response times. These programs focus on short latency responses, particularly those under 200ms, aiming to enhance explosive acceleration, position-specific directional changes, coordination, and cognitive motor functions. Unconscious reactions to sudden, potentially injurious perturbations—known as early latency responses—occur in as little as 50ms.

Gondwe et al.,(2024) estimate that non-contact ACL injuries often occur within 40ms after initial ground contact. This brief period is insufficient for the necessary postural corrections, reinforcing the argument that rehabilitation should incorporate elements of perception-action coupling. In contrast, traditional rehabilitation programs are limited to slower response training, requiring reaction times above 350ms. This limitation may not prepare athletes for the quick reactions needed in competitive environments, potentially contributing to high reinjury rates following ACLR (Bartels et al., 2016).

Bartels et al.,(2016) observed enhancements in both jump height and reaction time after athletes completed six SpeedCourt sessions. Given the critical appraisal rating, the results of this study should be interpreted with caution. Significant gaps and missing information raise concerns about the study's conduct and the reliability of its

findings. Although further research with larger sample groups and improved methodology is needed to fully assess the device's efficacy, the science and understanding behind the SpeedCourt device's mechanism of action are compelling. Traditional rehabilitation focuses on biomechanical changes observed in controlled laboratory settings, where interaction with the environment and external stimuli is limited. In contrast, the SpeedCourt device targets a neurocognitive principle known as perception-action coupling, which encourages athletes to consider both their own movement strategies and those of their opponents before executing an action. By integrating high-risk athletic manoeuvres with environmental perception, the SpeedCourt device may help bridge the gap between motor execution and isolated neurocognitive measures.

The rehabilitation opportunities provided by the SpeedCourt device appear to meet many essential criteria for effective motor learning. This device facilitates dual-tasking, promotes an EF, and supports implicit learning, self-controlled learning, visual-cognitive training, vestibular training, DL, movement variability and sensory reweighting. These elements work together to foster positive neuroplastic adaptations and enhance athletic performance. Clinicians utilizing the SpeedCourt can target one or more of these principles simultaneously, tailoring them to meet the sport-specific needs of the athletes undergoing rehabilitation (Bartels et al., 2016; Gondwe et al., 2024). Building on this, the scoping review by Deming and Groce (2023) found that most studies in their analysis concluded that patients undergoing ACLR demonstrated slower reaction times and diminished motor control when confronted with tasks that challenged cognitive, visual, and proprioceptive skills. These neural deficits caused patients to compensate with poor body mechanics, which increased their risk of reinjury. Incorporating these factors into ACLR rehabilitation protocols may improve RTP outcomes and lower the likelihood of reinjury.

In addition to the SpeedCourt device enhancing rehabilitation opportunities, it could also allow for the assessment of athletes under unpredictable, sport-specific change-of-direction movements (Ghrairi et al., 2023). Traditional RTP tests primarily evaluate physiological, biomechanical, and neuromuscular factors, often overlooking the

neurocognitive contributions to sports performance. While neurocognitive assessments are routinely included in RTP protocols following concussions, these evaluations are typically conducted using pen-and-paper or computer-based tests. This setup limits their relevance to sport-specific contexts, where transferring neurocognitive skills to actual performance is critical.

A systematic review by Losciale et al.,(2019) highlighted the limitations of traditional RTP testing, finding that these methods were ineffective in predicting reinjury risk. Although only four studies were included in the review—all of which were rated as low-quality evidence—these findings underscore the urgent need for more rigorous research to support RTP decisions. A systematic review by Ness et al.,(2020) explored the impact of adding cognitive load to single-leg stance and gait as a means of assessing neurocognitive reliance. While this research indicates promising progress, the authors emphasized that the types of motor and cognitive tasks, as well as the difficulty levels, are crucial factors in accurately evaluating dual-task performance outcomes.

Notably, the review included only a small number of studies, and none of them incorporated complex athletic movements reflective of the demands in competitive team sports, highlighting a gap in the current research. While further investigation is necessary, the SpeedCourt device shows promise as a potential solution to this challenge, as it can assess an athlete’s combined physical and neurocognitive capabilities at a more complex level. This integrated approach could facilitate a safer RTP while potentially lowering reinjury risk. By bridging the gap between motor skills and neurocognitive function, the SpeedCourt could enable more comprehensive assessments that incorporate open-skill motor tasks with cognitive demands—an aspect lacking in traditional RTP test batteries (Gondwe et al.,2024).

5.7 Perturbation training

An unexpected finding in this review was that adding perturbation training to a strength, agility, and secondary prevention program did not significantly enhance quadriceps strength or single-legged hop test scores. Additionally, no clinically meaningful differences were found in self-reported knee function or time from surgery to meeting RTP criteria. These results suggest that the addition of perturbation

training may not expedite an athlete's readiness to resume competitive activity. The perturbation exercises were adapted from a study by Fitzgerald et al. (2010), which focused on ACL-deficient (ACLD) rather than ACLR participants. In this study, participants who received perturbation training were nearly five times more likely to return successfully to high-level physical activity compared to those who only completed standard training.

The differences between Fitzgerald et al.'s (2010) results and those of the current review may be attributed to variations in participant eligibility criteria and execution of exercises in both the control and intervention groups. For instance, Arundale et al.,(2017) included only male participants, while evidence shows that females face a higher risk for ACL injury and reinjury, suggesting that gender differences are significant when analysing knee function post-surgery (Arundale et al., 2017). Moreover, Arundale et al.,(2017) included athletes 3 to 9 months post-ACLR, while Fitzgerald et al. focused on ACLD participants within six months of injury. Arundale et al.,(2017) noted that their broad enrolment window may have affected outcomes, as the time from completing training to the 1-year assessment varied. For example, those beginning training at 3 months might experience a larger treatment effect compared to those starting at 9 months. Additionally, a potential ceiling effect may have occurred because participants needed to achieve 80% limb symmetry to be included. While this selection ensured participants were prepared for high-level activities, this sample of men with relatively high baseline performance markers might have had limited room for further improvement.

Despite findings from the study by Arundale et al.,(2017), which showed no notable effect of perturbation training on RTP outcomes, the rationale behind perturbation training as a tool for promoting positive neuroplastic adaptations remains compelling. Research indicates that activating mechanoreceptors within joint structures can elevate gamma motor neuron activity, potentially enhancing the sensitivity of muscle spindles linked to the joint. This increased responsiveness may help prepare muscles to counter destabilizing forces, ultimately improving joint stability. When a force challenges the joint, muscles opposing that force are stretched and activated to resist it. Simultaneously, there's a reflexive inhibition of muscles that would pull in the same direction as the force, partially limiting unwanted stretch reflexes in these opposing muscles. This results in coordinated muscle activation around the joint, which stiffens

it and helps maintain stability under perturbation (Fitzgerald et al., 2010). This mechanism suggests that repeated perturbation training could foster beneficial reorganization in the CNS, potentially enhancing functional performance.

Recent evidence, such as the systematic review by Méndez-Bouza et al.,(2023), does not support perturbation training's effectiveness as a neuromuscular re-education method for accelerating RTP timelines after ACLR. Further research is essential to validate perturbation training's potential to induce neuroplastic changes. Based on motor learning and neuroplasticity principles outlined in the literature (Gokeler et al., 2019; Machan and Krupps, 2021; Wohl et al., 2021), it could be argued that perturbation training may not sufficiently engage the cortical pathways necessary to drive the neurocognitive and motor adaptations required for an earlier RTP.

5.7 Quality of evidence

A common limitation identified across four of the included studies (Ahmadi et al., 2020; Arundale et al., 2017; Ghaderi et al., 2021; Gholami et al., 2023) was the exclusive use of male participants, which limits the generalisability of these findings to female populations. This is particularly relevant given known sex-based differences in anatomical structure, hormonal influences, neuromuscular control, and recovery timelines—all of which can influence injury risk, rehabilitation outcomes, and motor learning responses (Griffin et al., 2006; Hewett et al., 2006; Myer et al., 2013). Despite this, the quality of evidence was rated highly for four of the six studies (Ahmadi et al., 2020; Arundale et al., 2017; Ghaderi et al., 2021; Gholami et al., 2023), while only two studies (Bartels et al., 2016; Kasmi et al., 2023) were rated as medium quality. This variation in study quality suggests that, while most of the evidence is robust, findings should still be interpreted with caution.

Chapter 6 Conclusion and Recommendations

6.1 Introduction

This review provides moderate evidence supporting the effectiveness of neuroplastic interventions in enhancing rehabilitation outcomes following anterior cruciate ligament reconstruction (ACLR). While no studies directly measured time to return-to-play (RTP) as a primary outcome, several neuroplastic interventions—specifically external focus of attention (EF), continuous cognitive tasks (CCT), differential learning (DL), and visuo-motor training (VMT)—demonstrated improvements in functional performance, postural control, dynamic balance, and psychological readiness. These factors are critical components of RTP clearance and suggest that such interventions may contribute to a faster and potentially safer return to sport when compared to standard rehabilitation alone.

Although the current evidence is insufficient to conclusively determine whether these interventions reduce reinjury rates, their positive influence on neuromechanical and cognitive variables associated with reinjury risk cannot be ignored. Traditional RTP assessments, which often overlook neurocognitive contributors to motor control, may fail to identify residual deficits that predispose athletes to secondary injury. As highlighted by Bartels et al. (2016), Machan and Krupps (2021), and Grooms et al. (2023), future RTP evaluations must evolve to include tools that assess neurocognitive function alongside biomechanics.

Innovative technologies such as the SpeedCourt, which integrates reactive agility and perception-action coupling, offer promising avenues for bridging the gap between physical and cognitive readiness. However, their utility remains underexplored in current literature.

It can therefore be concluded—albeit with moderate certainty—that neuroplastic rehabilitation interventions show greater clinical potential than traditional methods in accelerating RTP readiness following ACLR. However, this relationship has not yet been robustly quantified in terms of timeframes or reinjury rates, due to inconsistent outcome measures and a lack of long-term follow-up. More definitive evidence will

depend on future studies that apply sport-specific neuroplastic frameworks, employ consistent outcome measures, and include reinjury tracking over extended periods.

Despite the high methodological quality of the included studies, limitations such as small sample sizes, male-only cohorts, and heterogeneous interventions restrict generalisability. Greater collaboration across centres and sports is needed to refine treatment protocols and establish standardised outcome measures. Larger, multicentre trials in diverse athlete populations will be essential in confirming these early findings and guiding evidence-based RTP practices following ACLR.

6.2 Clinical/Practical Recommendations

This review highlights the need to reframe current approaches to ACLR rehabilitation. While traditional methods remain foundational, the findings suggest integrating neuroplasticity-based techniques to enhance central nervous system (CNS) adaptations. It is recommended that clinicians incorporate interventions that engage the visual, vestibular, and proprioceptive systems to improve motor control and postural stability.

There is compelling evidence that psychological support is crucial to optimizing motor performance during the rehabilitation process. Engaging a sports psychologist to address issues such as kinesiophobia and fear of reinjury may enhance athletes' readiness for RTP.

Rehabilitation milestones, which are often based solely on biological healing timelines, must prioritize cognitive and motor readiness. Instead of focusing only on the time since surgery, milestones should assess various measures of an athlete’s neurocognitive function. As rehabilitation progresses, exercises that encourage interaction with their environment are essential. These exercises should replicate the unpredictable, dynamic conditions of real-world sports to help bridge the gap between clinical settings and competitive play. Tools like the SpeedCourt for

example, allow athletes to practice decision-making and movement execution under conditions that closely mimic competition.

Finally, RTP criteria should be updated to better assess neurocognitive elements, including reaction time, visual-spatial processing, and postural stability. This approach offers a more comprehensive view of an athlete's readiness to safely return to their sport, addressing both physical recovery and the necessary neural adaptations

6.3 Recommendation for Future Research

Given the limited research on neuroplasticity in ACL rehabilitation within sport-specific settings, there is a pressing need for larger, multicentre trials that focus specifically on neuroplastic rehabilitation. Such studies should aim to establish a sound evidence base for the selection of effective neuroplastic exercises, along with clearly defined parameters for dosage and progression, enabling more precise and clinically applicable rehabilitation prescriptions. Consistency in outcome reporting is essential for meaningful comparisons and meta-analyses, as this will contribute significantly to the growing evidence base. In particular, the RTP timeframe should be a primary outcome measure, as it may help gauge the effectiveness of neuroplastic interventions in potentially accelerating recovery following ACLR compared to traditional rehabilitation.

Collaboration among ACLR researchers is essential to develop comparable treatment protocols, shared outcome measures, and standardized reporting practices. Additionally, these studies would benefit from adequate follow-up periods to assess the long-term impact of interventions—particularly with respect to reinjury rates and the development of pathologic sequelae such as chronic knee instability, early-onset osteoarthritis, and persistent neuromuscular deficits.
The evidence from this review strongly supports the use of neuroplastic techniques in ACLR rehabilitation, underscoring an urgent need for standardized protocols. Developing these protocols would enable more consistent treatment practices and

help identify best practice across varied athletic populations, creating a foundation for rehabilitation that is both personalized and effective.

Finally, further research is crucial to improve methods for assessing neurocognitive function and to gain a deeper understanding of neural adaptations post-ACLR.

6.4 Strengths and Limitations

The main strength of this review lies in the high quality of evidence from most of the included studies, enhancing the reliability of the findings. The comprehensive literature review conducted at the outset also allowed for thorough contextualization of results within existing research, contributing to robust conclusions.

However, several limitations are present. The review included only six studies, and although broad inclusion criteria allowed for diversity in sport type, notable heterogeneity—such as variation in participant demographics, outcome measures, follow-up durations, competition levels, and intervention types—still complicated direct comparisons and limited the ability to draw consistent conclusions across studies. Additionally, restricting participant eligibility to “athletes” may have limited the inclusion of valuable evidence from broader studies that may have referred to participants as “patients.”

This review included studies involving athletes of varying ages, sexes, ethnicities, and sporting contexts. While this diversity increases the generalizability of the findings, it also introduces clinical heterogeneity that may influence neuroplastic adaptations and motor learning outcomes. Differences in neuroplastic potential and recovery profiles between demographic groups could have affected study outcomes. However, due to the relatively limited body of literature on neuroplastic interventions in ACL rehabilitation (predominantly emerging after 2013), applying narrower inclusion criteria would likely have excluded valuable data. Until the field matures and more targeted studies are available, broader inclusion criteria were deemed necessary to ensure a comprehensive synthesis of current evidence.

Additionally, by including only studies that investigated isolated ACL injuries and excluding cases with concurrent meniscal, MCL, or chondral damage, the review may not fully represent the broader ACLR population encountered in clinical practice. This decision was made to minimise confounding and improve internal validity, but it limits the generalizability of the findings.

The restriction to English-language publications within a specified date range may have constrained the search results, potentially overlooking relevant studies. None of the studies used time from surgery to RTP as a direct outcome measure, which constrains the ability to draw definitive conclusions on the effectiveness of neuroplastic interventions in reducing RTP timeframes. Finally, without statistical pooling, a meta-analysis could not be conducted, and a narrative synthesis was used instead, which may have limited the overall strength of the conclusions.

Furthermore, the outcome measures used in the included studies primarily evaluated functional performance, rather than directly measuring neuroplastic adaptations. This may limit the review's ability to fully capture the central effects of the interventions. At present, few outcome tools have been developed or validated to assess neuroplastic changes specifically in orthopaedic or sports rehabilitation (Grooms et al., 2015). Future research should focus on establishing such measures. Until then, it is inferred that improvements in physical function may act as indirect indicators of neuroplastic recovery.

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Appendices

Appendix A: Excluded studies and reasons for exclusion

Population/Participant Characteristics
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Appendix B: Search strategies for individual databases

The following databases were searched on May 22, 2024 (unless stated otherwise) to identify studies published in the literature.

Database	Search strategy/Keywords/Parameters	Results
Cinahl Complete	ACL OR “anterior cruciate ligament” OR “anterior cruciate ligament injuries” OR “ACL injuries” OR “anterior cruciate ligament reconstruction” OR “ACL reconstruction” OR “anterior cruciate ligament repair” OR “ACL repair” OR “anterior cruciate ligament surgery” OR “ACL surgery” OR “anterior cruciate ligament reconstruction” OR “ACL surgical reconstruction” AND “central nervous system” OR brain OR neuroscience OR neuroplasticity OR “neuroplastic processes” OR “neuronal plasticity” OR “motor control” OR “motor control/learning” OR “motor learning” OR “motor learning strategy” OR “motor learning principles” OR “principles of motor learning” OR “movement variability” OR “kinematic variability” OR “neuromuscular control” OR “sensory reweighting” AND “subsequent ACL injury” OR “subsequent anterior cruciate ligament injury” OR “second anterior cruciate ligament injury risk” OR “second ACL injury risk” OR “secondary injury” OR reinjury OR reinjuries AND rehabilitation OR “therapeutic intervention” OR “exercise therapy” OR treatment AND “return to sport” OR “return to performance” OR “return to play” AND athletes OR “elite athletes” OR “professional athletes”	0
ClinicalKey	ACL OR “anterior cruciate ligament” OR “anterior cruciate ligament injuries” OR “ACL injuries” OR “anterior cruciate ligament reconstruction” OR “ACL reconstruction” OR “anterior cruciate ligament repair” OR “ACL repair” OR “anterior cruciate ligament surgery” OR “ACL surgery” OR “anterior cruciate ligament reconstruction” OR “ACL surgical reconstruction” AND “central nervous system” OR brain OR neuroscience OR neuroplasticity OR “neuroplastic processes” OR “neuronal plasticity” OR “motor control” OR “motor control/learning” OR “motor learning” OR “motor learning strategy” OR “motor learning principles” OR “principles of motor learning” OR “movement variability” OR “kinematic variability” OR “neuromuscular control” OR “sensory reweighting” AND “subsequent ACL injury” OR “subsequent anterior cruciate ligament injury” OR “second anterior cruciate ligament injury risk” OR “second ACL injury risk” OR “secondary injury” OR reinjury OR reinjuries AND rehabilitation OR “therapeutic intervention” OR “exercise therapy” OR treatment AND “return to sport” OR “return to performance” OR “return to play” AND athletes OR “elite athletes” OR “professional athletes”	14

Cochrane	ACL OR “anterior cruciate ligament” OR “anterior cruciate ligament injuries” OR “ACL injuries” OR “anterior cruciate ligament reconstruction” OR “ACL reconstruction” OR “anterior cruciate ligament repair” OR “ACL repair” OR “anterior cruciate ligament surgery” OR “ACL surgery” OR “anterior cruciate ligament reconstruction” OR “ACL surgical reconstruction” AND “central nervous system” OR brain OR neuroscience OR neuroplasticity OR “neuroplastic processes” OR “neuronal plasticity” OR “motor control” OR “motor control/learning” OR “motor learning” OR “motor learning strategy” OR “motor learning principles” OR “principles of motor learning” OR “movement variability” OR “kinematic variability” OR “neuromuscular control” OR “sensory reweighting” AND “subsequent ACL injury” OR “subsequent anterior cruciate ligament injury” OR “second anterior cruciate ligament injury risk” OR “second ACL injury risk” OR “secondary injury” OR reinjury OR reinjuries AND rehabilitation OR “therapeutic intervention” OR “exercise therapy” OR treatment AND “return to sport” OR “return to performance” OR “return to play” AND athletes OR “elite athletes” OR “professional athletes”	6
PEDro	"anterior cruciate ligament reconstruction and neuroplasticity"	17
	"anterior cruciate ligament reconstruction"	
	"anterior cruciate ligament reconstruction and motor learning"	
	"neuroplasticity"	
	"motor learning"	
ProQuest	ACL OR “anterior cruciate ligament” OR “anterior cruciate ligament injuries” OR “ACL injuries” OR “anterior cruciate ligament reconstruction” OR “ACL reconstruction” OR “anterior cruciate ligament repair” OR “ACL repair” OR “anterior cruciate ligament surgery” OR “ACL surgery” OR “anterior cruciate ligament reconstruction” OR “ACL surgical reconstruction” AND “central nervous system” OR brain OR neuroscience OR neuroplasticity OR “neuroplastic processes” OR “neuronal plasticity” OR “motor control” OR “motor control/learning” OR “motor learning” OR “motor learning strategy” OR “motor learning principles” OR “principles of motor learning” OR “movement variability” OR “kinematic variability” OR “neuromuscular control” OR “sensory reweighting” AND “subsequent ACL injury” OR “subsequent anterior cruciate ligament injury” OR “second anterior cruciate ligament injury risk” OR “second ACL injury risk” OR “secondary injury” OR reinjury OR reinjuries AND rehabilitation OR “therapeutic intervention” OR “exercise therapy” OR treatment AND “return to sport” OR “return to performance” OR “return to play” AND athletes OR “elite athletes” OR “professional athletes”	49
ProQuest Theses and	ACL OR “anterior cruciate ligament” OR “anterior cruciate ligament injuries” OR “ACL injuries” OR “anterior cruciate ligament reconstruction” OR “ACL reconstruction” OR “anterior cruciate ligament repair” OR “ACL repair” OR “anterior cruciate ligament surgery” OR “ACL surgery” OR “anterior cruciate	100

Dissertations Global	ligament reconstruction” OR “ACL surgical reconstruction” AND “central nervous system” OR brain OR neuroscience OR neuroplasticity OR “neuroplastic processes” OR “neuronal plasticity” OR “motor control” OR “motor control/learning” OR “motor learning” OR “motor learning strategy” OR “motor learning principles” OR “principles of motor learning” OR “movement variability” OR “kinematic variability” OR “neuromuscular control” OR “sensory reweighting” AND “subsequent ACL injury” OR “subsequent anterior cruciate ligament injury” OR “second anterior cruciate ligament injury risk” OR “second ACL injury risk” OR “secondary injury” OR reinjury OR reinjuries AND rehabilitation OR “therapeutic intervention” OR “exercise therapy” OR treatment AND “return to sport” OR “return to performance” OR “return to play” AND athletes OR “elite athletes” OR “professional athletes”	
Pubmed	""anterior cruciate ligament""[MeSH Terms] OR (""anterior""[All Fields] AND ""cruciate""[All Fields] AND ""ligament""[All Fields]) OR ""anterior cruciate ligament""[All Fields] OR ""acl""[All Fields] OR ""anterior cruciate ligament""[All Fields] OR ""anterior cruciate ligament injuries""[All Fields] OR ""ACL injuries""[All Fields] OR ""anterior cruciate ligament reconstruction""[All Fields] OR ""ACL reconstruction""[All Fields] OR ""anterior cruciate ligament repair""[All Fields] OR ""ACL repair""[All Fields] OR ""anterior cruciate ligament surgery""[All Fields] OR ""ACL surgery""[All Fields] OR ""anterior cruciate ligament reconstruction""[All Fields] OR ""ACL surgical reconstruction""[All Fields]) AND ""central nervous system""[All Fields]) OR (""brain""[MeSH Terms] OR ""brain""[All Fields] OR ""brains""[All Fields] OR ""brain s""[All Fields]) OR (""neuroscience s""[All Fields] OR ""neurosciences""[MeSH Terms] OR ""neurosciences""[All Fields] OR ""neuroscience""[All Fields]) OR (""neuronal plasticity""[MeSH Terms] OR (""neuronal""[All Fields] AND ""plasticity""[All Fields]) OR ""neuronal plasticity""[All Fields] OR ""neuroplasticity""[All Fields] OR ""neuroplastic""[All Fields]) OR ""neuroplastic processes""[All Fields] OR ""neuronal plasticity""[All Fields] OR ""motor control""[All Fields] OR ""motor control/learning""[All Fields] OR ""motor learning""[All Fields] OR ""motor learning strategy""[All Fields] OR ""motor learning principles""[All Fields] OR ""principles of motor learning""[All Fields] OR ""movement variability""[All Fields] OR ""kinematic variability""[All Fields] OR ""neuromuscular control""[All Fields] OR ""sensory reweighting""[All Fields]) AND ""subsequent ACL injury""[All Fields]) OR ""subsequent anterior cruciate ligament injury""[All Fields] OR ""second anterior cruciate ligament injury risk""[All Fields] OR ""second ACL injury risk""[All Fields] OR ""secondary injury""[All Fields] OR (""reinjuries""[MeSH Terms] OR ""reinjuries""[All Fields] OR ""reinjury""[All Fields]) OR (""reinjuries""[MeSH Terms] OR ""reinjuries""[All Fields] OR ""reinjury""[All Fields])) AND (""rehabilitant""[All Fields] OR ""rehabilitants""[All Fields] OR ""rehabilitate""[All Fields] OR ""rehabilitated""[All Fields] OR ""rehabilitates""[All Fields] OR ""rehabilitating""[All Fields] OR ""rehabilitation""[MeSH Terms] OR ""rehabilitation""[All Fields] OR ""rehabilitations""[All Fields] OR ""rehabilitative""[All Fields] OR ""rehabilitation""[MeSH Subheading] OR	700

	""rehabilitation s""[All Fields] OR ""rehabilitational""[All Fields] OR ""rehabilitator""[All Fields] OR ""rehabilitators""[All Fields])) OR ""therapeutic intervention""[All Fields] OR ""exercise therapy""[All Fields] OR (""therapeutics""[MeSH Terms] OR ""therapeutics""[All Fields] OR ""treatments""[All Fields] OR ""therapy""[MeSH Subheading] OR ""therapy""[All Fields] OR ""treatment""[All Fields] OR ""treatment s""[All Fields])) AND ""return to sport""[All Fields]) OR ""return to performance""[All Fields] OR ""return to play""[All Fields]) AND (""athlete s""[All Fields] OR ""athletes""[MeSH Terms] OR ""athletes""[All Fields] OR ""athlete""[All Fields] OR ""athletically""[All Fields] OR ""athlets""[All Fields] OR ""sports""[MeSH Terms] OR ""sports""[All Fields] OR ""athletic""[All Fields] OR ""athletics""[All Fields])) OR ""elite athletes""[All Fields] OR ""professional athletes""[All Fields])	
	""anterior cruciate ligament""[MeSH Terms] OR (""anterior""[All Fields] AND ""cruciate""[All Fields] AND ""ligament""[All Fields]) OR ""anterior cruciate ligament""[All Fields] OR ""acl""[All Fields] OR ""anterior cruciate ligament""[All Fields] OR ""anterior cruciate ligament injuries""[All Fields] OR ""ACL injuries""[All Fields] OR ""anterior cruciate ligament reconstruction""[All Fields] OR ""ACL reconstruction""[All Fields] OR ""anterior cruciate ligament repair""[All Fields] OR ""ACL repair""[All Fields] OR ""anterior cruciate ligament surgery""[All Fields] OR ""ACL surgery""[All Fields] OR ""anterior cruciate ligament reconstruction""[All Fields] OR ""ACL surgical reconstruction""[All Fields]) AND ""central nervous system""[All Fields]) OR (""brain""[MeSH Terms] OR ""brain""[All Fields] OR ""brains""[All Fields] OR ""brain s""[All Fields]) OR (""neuroscience s""[All Fields] OR ""neurosciences""[MeSH Terms] OR ""neurosciences""[All Fields] OR ""neuroscience""[All Fields]) OR (""neuronal plasticity""[MeSH Terms] OR (""neuronal""[All Fields] AND ""plasticity""[All Fields]) OR ""neuronal plasticity""[All Fields] OR ""neuroplasticity""[All Fields] OR ""neuroplastic""[All Fields]) OR ""neuroplastic processes""[All Fields] OR ""neuronal plasticity""[All Fields] OR ""motor control""[All Fields] OR ""motor control/learning""[All Fields] OR ""motor learning""[All Fields] OR ""motor learning strategy""[All Fields] OR ""motor learning principles""[All Fields] OR ""principles of motor learning""[All Fields] OR ""movement variability""[All Fields] OR ""kinematic variability""[All Fields] OR ""neuromuscular control""[All Fields] OR ""sensory reweighting""[All Fields]) AND ""subsequent ACL injury""[All Fields]) OR ""subsequent anterior cruciate ligament injury""[All Fields] OR ""second anterior cruciate ligament injury risk""[All Fields] OR ""second ACL injury risk""[All Fields] OR ""secondary injury""[All Fields] OR (""reinjuries""[MeSH Terms] OR ""reinjuries""[All Fields] OR ""reinjury""[All Fields]) OR (""reinjuries""[MeSH Terms] OR ""reinjuries""[All Fields] OR ""reinjury""[All Fields])) AND (""rehabilitant""[All Fields] OR ""rehabilitants""[All Fields] OR ""rehabilitate""[All Fields] OR ""rehabilitated""[All Fields] OR ""rehabilitates""[All Fields] OR ""rehabilitating""[All Fields] OR ""rehabilitation""[MeSH Terms] OR ""rehabilitation""[All Fields] OR ""rehabilitations""[All Fields] OR ""rehabilitative""[All Fields] OR ""rehabilitation""[MeSH Subheading] OR ""rehabilitation s""[All Fields] OR ""rehabilitational""[All Fields] OR ""rehabilitator""[All Fields] OR	

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ScienceDirect	"Anterior cruciate ligament reconstruction" AND "neuroplasticity OR "motor learning" AND "rehabilitation" AND "return to play"	25
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	"Anterior cruciate ligament reconstructions" AND "neuroplasticity OR "motor learning" AND "return to sport"	
	"Anterior cruciate ligament" OR "anterior cruciate ligament reconstruction" AND "neuroplasticity OR "motor learning" AND "return to sport"	
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Scopus	ACL OR'anterior cruciate ligament' OR 'anterior cruciate ligament injuries' OR 'ACL injuries' OR 'anterior cruciate ligament reconstruction' OR 'ACL reconstruction' OR 'anterior cruciate ligament repair' OR 'ACL repair' OR 'anterior cruciate ligament surgery' OR 'ACL surgery' OR 'anterior cruciate ligament reconstruction' OR 'ACL surgical reconstruction' AND 'central nervous system' OR brain OR neuroscience	925

	OR neuroplasticity OR 'neuroplastic processes' OR 'neuronal plasticity' OR 'motor control' OR 'motor control/learning' OR 'motor learning' OR 'motor learning strategy' OR 'motor learning principles' OR 'principles of motor learning' OR 'movement variability' OR 'kinematic variability' OR 'neuromuscular control' OR 'sensory reweighting' AND 'subsequent ACL injury' OR 'subsequent anterior cruciate ligament injury' OR 'second anterior cruciate ligament injury risk' OR 'second ACL injury risk' OR 'secondary injury' OR reinjury OR reinjuries AND rehabilitation OR 'therapeutic intervention' OR 'exercise therapy' OR treatment AND 'return to sport' OR 'return to performance' OR 'return to play' AND athletes OR 'elite athletes' OR 'professional athletes'	
SportDISCUS	ACL OR “anterior cruciate ligament” OR “anterior cruciate ligament injuries” OR “ACL injuries” OR “anterior cruciate ligament reconstruction” OR “ACL reconstruction” OR “anterior cruciate ligament repair” OR “ACL repair” OR “anterior cruciate ligament surgery” OR “ACL surgery” OR “anterior cruciate ligament reconstruction” OR “ACL surgical reconstruction” AND “central nervous system” OR brain OR neuroscience OR neuroplasticity OR “neuroplastic processes” OR “neuronal plasticity” OR “motor control” OR “motor control/learning” OR “motor learning” OR “motor learning strategy” OR “motor learning principles” OR “principles of motor learning” OR “movement variability” OR “kinematic variability” OR “neuromuscular control” OR “sensory reweighting” AND “subsequent ACL injury” OR “subsequent anterior cruciate ligament injury” OR “second anterior cruciate ligament injury risk” OR “second ACL injury risk” OR “secondary injury” OR reinjury OR reinjuries AND rehabilitation OR “therapeutic intervention” OR “exercise therapy” OR treatment AND “return to sport” OR “return to performance” OR “return to play” AND athletes OR “elite athletes” OR “professional athletes”	4

Appendix C: Characteristics of included studies

Study	Design/study type	Country	Setting/context	Outcomes measured	Follow-up	Participants	Intervention (I) and comparator (C)			Critical appraisal rating
							Components	Duration and frequency	Delivered by	
(Ahmadi et al., 2020)	Analytical cross-sectional study	Iran	Very little information given about setting or context. Study was carried out in Iran, using athlete's/soccer players as participants.	Dependent variables included area of 95 % confidence ellipse, standard deviation (SD) of COP in anterior-posterior (AP) and medial-lateral (ML) directions, mean velocity of COP in AP and ML directions, and Mean Power Frequency (MPF) in AP and ML directions. These variables were used to measure linear centre of pressure in order to assess static standing balance and dynamic postural sway.	N/A	All ACLR participants had been involved in regular soccer activity prior to their injury. The healthy subjects were matched with ACL-R athletes in terms of their age, height, weight, activity level, education level and leg dominancy. The ACLR group used participants with an average age of 26.55 years, an average height of 179.15cm, an average weight of 78.10kg, an average BMI of 24.43kg/m2, an average educational level of 13 years and a Tegner activity rating of 8.60. ACLR participants were also evaluated using the KOOS score which showed that all of them were free of pain, had returned to full ADL's and sports and recreation. On average their symptom score was 98.85/100 indicating a few remaining symptoms of disability and their quality of life was rated as 98.80/100 indicating a good quality of life for most participants. The healthy participants without any injury or musculoskeletal disorder had an average age of 25.95 years, an average height of 177.95cm, an average weight of 74.30kg, an average BMI of 23.61kg/m2, an average educational level of 12.60 years and a Tegner activity rating of 8.80. The healthy participants were not required to do an evaluation of disability using the KOOS. **Group Description and sample (1)** ACL-R group: 20 soccer players with arthroscopic unilateral autogenous hamstring tendon graft. (14.10 ± 3.99 months after surgery). From the ACL-R people, 15 subjects had surgery on the dominant leg and 5 subjects had surgery on the non-dominant leg **Group description and sample (2)** Control group: 20 soccer players with no injury or musculoskeletal disorder that could impair their postural control	**I1:External focus of attention** The participants were asked to stand on their operated leg and focus on minimizing the movement of the bubble marker at the origin of coordinates. Using an application image on the screen would increase the adherence of the subjects to keep their focus on the bubble marker's movement. **I2: Continuous cognitive task** The participants were asked to stand on a single leg while performing a sequence continuous task. The sequence continuous task comprised of mentally counting the number of times a randomly selected digit (1–9) was occurred in 20 sets of three-digit numbers each presented at a 3-second interval (e.g. count the number of times 2 was occurred in the following sequences: 221, 326, 471, etc.) C: Normal control of their balance while standing on a wobble board.	Before the test, the participants performed one familiarization trial (60s) in every condition. To evaluate postural control, the participants were asked to stand on their operated leg (60s) with full-extended knee and arms hanging on the sides such that the contralateral leg was semi-flexed.	Not clear. "We used a Thera Band black Wobble Board placed on the force plate to evaluate postural control in a dynamic situation." The "we" may be referring to the researchers themselves, but no clarity is given on this.	6/8 = high quality of evidence
(Gholami et al., 2023)	Randomized controlled trial	Iran	The study was conducted in the biomechanics lab of the Kharazmi University, Iran, from March of 2020 to July of 2020.	-Functional performance (triple hop test) -Dynamic balance during the Star Excursion Balance Test -Biomechanics during single leg drop jump (knee flexion (KF), ankle dorsiflexion (AD), knee valgus (KV), and vertical ground reaction force (VGRF)) -Kinesiophobia (Tampa Scale of Kinesiophobia) Baseline and post-intervention outcomes were measured by two blinded assessors.	8 weeks	All participants were males who played competitive handball, volleyball and basketball and had had an ACL reconstruction performed by the same surgeon within 6-12 months prior to participation in the study. All participants had been cleared by their medical teams to resume sports participation. The participants in the DL group had an average age of 28.8 years, an average height of 175.2cm, an average weight of 78.4kg, an average BMI of 22.4kg/m2, and an average "time since surgery" of 8.5 months. The participants in the VMT group had an average age of 29.1 years, an average height of 174cm, an average weight of 77kg, an average BMI of 22.1kg/m2, and an average "time since surgery" of 8.8 months. The participants in the control group had an average age of 27.9 years, an average height of 174.3cm, an average weight of 79kg, an average BMI of 22.6kg/m2, and an average "time since surgery" of 7.8 months. **Group Description and sample (1)** Intervention 1 – Differential learning (DL):	**I1: Differential learning** The exercises were performed under different conditions (Table 2), including exercises in the dark, on the sand with shoes and without shoes, and with loud music. Additionally, variations of the double-legged jump were included, e.g., double legged jump on a Bosu-ball, double-legged jump over an obstacle, and double-legged jump with an air target. **I2: Visual-motor Training** VMT protocols were developed for stroboscopic intervention and integrated into regular training (Table 3). The VMT protocols consisted of tasks including a Tap-test, agility ladder drills, single-leg stance (on foam), vertical jumps, and squat jumps. In addition, an error scoring system with detailed criteria to assess behavioural performance while wearing	I1: Exercises executed for 8 weeks under the supervision of an experienced athletic trainer. Each wee comprised three sessions of 25-30 min on odd days. I2: 8-week training period, consisting of three sessions per week (even days), with every training session lasting approximately 25-30 min. C: Athletes were encouraged to continue their typical training regimen. No further details of	According to the group assignment, a researcher blinded to the baseline assessments proceeded with training.	10/13 – High quality of evidence

						•15 participants **Group description and sample (2)** Intervention 2 – Visuomotor training (VMT): •15 participants **Group description and sample (3)** Control group: •15 participants	stereoscopic glass (SG) is described in Table 4 **C: Typical training regimen**, such as improving technique and sport-related skills.	dosage and frequency provided for this group.		
(Kasmi et al., 2023)	Randomized controlled trial	Tunisia	Elite male athletes from different sports who had all sustained an ACL injury underwent surgery at the Hospital Ortopedico (Allysa, Tunisia) by two knee surgeons who had 20 years of technical experience with ACL reconstructions.	•Psychological kinesiophobia status (Tampa kinesiophobia score) •Functional knee assessment (KOOS score and IKDC score) •Isokinetic muscle strength performance (LSI, Peak torque (PT), the total work (TW) & ratio- HQ, ratio -TW at different angular velocities measured in knee flexors and extensors by isokinetic testing)	6 weeks	All participants were elite male athletes who performed systematic sports on an international level and were members of the Tunisian national team in their respective sport. They were athletes who practiced their sport for more than 10 years and exercised between 6 and 8 times per week including competition. They had all sustained a non-contact ACL injury during their sporting activity, either training or competition. 8 of the participants in each group were involved with team sports, and 2 were involved with individual sports. All participants completed an average of 7 training sessions per week. The dominant side of participants across all groups was varied. The participants in the CON group had an average age of 20.4 years, an average height of 179.6cm, an average weight of 75.50g and an average BMI of 20.95kg/m2. Of this group, 6 participants were R side dominant, and 4 were left side dominant. Across all the following intervention groups, 8 of the participants were R handed and 2 were left handed. The participants in the ECC group had an average age of 20.3 years, an average height of 180.40cm, an average weight of 20.30kg, and an average BMI of 21.59kg/m2. The participants in the PLYO group had an average age of 20.30 years, an average height of 179.50cm, an average weight of 78.2kg, and an average BMI of 21.68kg/m2. The participants in the COMB group had an average age of 20.60 years, an average height of 184.00cm, an average weight of 79.50kg and an average BMI of 21.56kg/m2. **Group Description and sample (1)** Intervention 1 – Single-mode Eccentric group (ECC) •10 athletes **Group description and sample (2)** Intervention 2 – Single-mode Plyometric group (PLYO) •10 athletes **Group description and sample (3)** Intervention 3 – Combined eccentric and plyometric group (COMB) •10 athletes **Group description and sample (4)** Control group – Traditional rehabilitation program •10 athletes	**I1: Eccentric** **I2: Plyometric** **I3:Combination (eccentric and plyometric):** **C: Traditional rehabilitation program** consisting of flexibility, balance (i.e., bibedal and unipedal stance) and submaximal running exercises	All intervention groups: All participants performed two weekly training sessions over a 6-weeks intervention period with 60 min per session and an overall number of 12 training sessions in addition to the traditional program. The training volume (training weeks, sets, repetitions, and duration) was equal between the intervention group and the control groups. Each training session started with a standardized 15-minute warm-up, including submaximal intensity running, dynamic stretching, calisthenics, and preparatory exercises (eg. Balance and landing, squatting, jumping exercises) at a progressively increased intensity. i	Training was delivered by expert strength and conditioning coaches from the National Medical Sports Center of Tunisia.	9/13 = medium to high quality of evidence
(Bartels et al., 2016)	Randomized controlled trial	Germany	Very little information given about the study setting and context, however the SpeedCourt-interactive training device was developed in Hemsbach, Germany and the study also	Anthropometric parameters: The dimensions of the upper and lower leg were measured. This was conducted using metric tape 15 and 10 cm above, at 15 and 10 cm below joint-line.	3 weeks	50 active and sportive patients were used in this study. All participants had undergone an ACL reconstruction 5 months prior to the start of the study. The 28 participants in the SpeedCourt group had an average age of 31.4 years, an average height of 1.75m, an average weight of 76.30kg and an average BMI of	**I: SpeedCourt training** The SpeedCourt training consists of 5–6 exercises which last between 15 and 30 s. Every exercise was repeated thrice. The pause lengths showed inter-individual differences depending on the resilience of the patient. Generally the pause lengths were four times as long	The training (I & C) lasted for a duration of 3 weeks, twice a week.	Not reported	6/13 = medium quality of evidence

			appeared to be carried out in Germany.	Sports performance tests: •Total range of motion in flexion and extension (tROM) •Finger-ground distance •Reaction time •Ground contact time •Tapping (time interval 3sec) •Jump height (uni- and bi-lateral) •Jump width (bilateral). All tests were supervised from one examiner and senior member of the study group.		24.7kg/m2. Of this group, 6 were female and 22 were males. The 22 participants in the regular and stabilizing group had an average age of 34.4 years, an average height of 1.78m, an average weight of 75.40kg and an average BMI of 23.8kg/m2. Of this group, 8 were female and 14 were males. The anthropometric data showed no significant differences between the groups. **Group Description and sample (1)** Intervention – SpeedCourt training •28 patient's **Group description and sample (2)** Control group – Regular coordinative and stabilizing program •22 patient's	as the original exercise. The exercises comprised mostly running actions which were incidentally computer generated. Some of them were also color coded, which were matched to different tasks (yellow: jog twice around the field; blue: run to the opposite field). **C: The stabilization training** was standardized. Different unstable and uneven surfaces were incorporated (Posturomed, Slashpipe, BOSU, Airex, Kippelbrett, Pezziball, Stepper). Every exercise was completed in 30 s. A 30-s pause was allowed and then the exercise was performed with the contralateral side. During every training, 30 min consisted of the exercises for stabilization.			
(Ghaderi et al., 2021)	Randomized controlled trial	Iran	No information is given with regards to setting or context of the study.	•Biomechanics testing Kinematic data: Peak trunk flexion, peak hip flexion, peak knee flexion, peak knee abduction, peak knee internal rotation) Kinetic data: Peak reaction force, peak anterior tibial shear force, peak knee extension moment, peak knee abduction moment, loading rate •Knee joint position sense (using isokinetic dynamometer) •Patient-reported function (Persian version of the IKDC form) The second licensed athletic trainer involved in the study carried out the baseline assessments.	8 weeks	All participants were male and had undergone a successful primary, unilateral ACL reconstruction performed by the same surgeon 6-12 months prior to study commencement. All participants had been cleared to resume sports participation by their medical team. The control group used participants with an average age of 27.2 years, an average height of 1.7m, an average weight of 70.1kg, an average BMI of 23.2kg/m2, an average time since surgery of 7.5 months and a Tegner activity rating of 4.5. The experimental group used participants with an average age of 26.9 years, an average height of 1.8m, an average weight of 70.3kg, an average BMI of 22.7kg/m2, an average time since surgery of 7.8 months and a Tegner activity rating of 6. **Group Description and sample (1)** Control group: •12 participants **Group description and sample (2)** Experimental group: •12 participants	**I: Neuromuscular training program** Eight exercises were performed as part of the program: double-leg squats, walking lunges, single-leg squats, double-leg drop jumps, single-leg stance on an unstable surface, single-leg countermovement jumps, horizontal bounds, and single-leg standing long jumps. All exercises were performed with bodyweight resistance. Throughout training, the trainer provided athletes with standard instructions/cues regarding their technique in order to maximize the effectiveness of the program. The specific instructions for each exercise were based on those proposed by Benjaminse et al. (2015) [30]. and were intended to promote an external focus of attention, which has been shown to result in better performance and retention of learned movement patterns for a wide-range of movement tasks (vs. an internal focus) C: Routine activities which focused on sport-specific skills training over the same 8-week period but did not receive any formal neuromuscular training.	Athletes completed sessions per week for weeks 1-6 and 2 sessions per week for weeks 7 and 8 (22 total sessions)	The 'third' experienced athletic trainer involved in the study.	12/13 - high quality of evidence
(Arundale et al., 2017)	Randomized controlled trial	USA	The Anterior Cruciate Ligament-Specialized Post-Operative Return-to-Sports (ACL-SPORTS) training program was developed as a means to prepare athletes to successfully return to preinjury activities, improve limb symmetry, and address postoperative neuromuscular impairments and predictors of a second knee injury. It is common in the United States for athletes after ACL reconstruction to be discharged from physical	Functional testing: •Quadriceps strength (electromechanical dynamometer) •Quadriceps strength limb symmetry •Limb symmetry indices (LSI) •Single-legged hop testing IKDC form KOOS-Sports and recreation subscale KOOS-quality-of-life subscale Researchers and physical therapists that were blind to group assignment performed data collection and analysis.	5 weeks after completion of ACL SPORTS training program, and 1 year and 2 years after ACL reconstruction.	Of 113 athletes screened, 40 athletes were enrolled into the ACL-SPORTS training program and completed all 10 sessions of training. All participants in this study were male and had all undergone an isolated unilateral ACL reconstruction by 21 different experienced sports orthopaedic surgeons. Prior to their injuries, all athletes had participated in Level 1 or Level 2 sports >50 hours/year and desired to return to their preinjury activity levels. All participants had already completed 3-9 months of outpatient rehabilitation. The SAP group used participants with an average age at surgery of 24 years, an average height of 179cm, an average weight of 86kg and an average time from surgery to enrolment in the ACL-SPORTS training protocol of 23 weeks. Of this group, 14 participants	**I: SAP+PERT (perturbation):** Athletes received all of the same exercises as the SAP groups augmented with perturbation training. The addition of perturbation training was used to target neuromuscular impairments including muscle co-contraction and abnormal knee kinematics and kinetics **C: SAP (strengthening, agility, prevention):** The SAP group received progressive secondary ACL injury prevention exercises and agility drills. Quadriceps femoris muscle strengthening exercises were also included for athletes whose quadriceps strength symmetry	The ACL SPORTS training program included 10 treatment sessions (two times per week for 5 weeks) for all athletes.	Not reported	10/13 – high quality of evidence

			therapy at the point they achieve activities of daily living goals and basic athletic tasks such as running. Thus, to capture this population and time point as well as allow for the results of this study to be generalizable, rehabilitation before the ACL-SPORTS training program was not standardized and was performed in a number of different community physical therapy clinics.			had an autograft and 6 participants had an allograft. 9 participants had sustained injury through a mechanism of contact, while 11 participants had sustained injury through a mechanism of non-contact. The SAP+PERT group used participants with an average age at surgery of 23 years, an average height of 177cm, an average weight of 86kg and an average time from surgery to enrolment in the ACL-SPORTS training protocol of 22 weeks. Of this group, 13 participants had an autograft and 7 participants had an allograft. 9 participants had sustained injury through a mechanism of contact, while 11 participants had sustained injury through a mechanism of non-contact. **Group Description and sample (1)** SAP group: •20 participants **Group description and sample (2)** SAP + PERT group: •20 participants	measures were between 80% and 90% to help athletes achieve the return to sport criteria of 90% quadriceps strength limb symmetry [40]. Collectively, these exercises were determined to target impairments in balance, dynamic sport-related tasks, and muscle strength, all of which are risk factors for initial ACL injury [29, 30] and subsequent reinjury.			

The studies summarised in Appendix C demonstrate marked heterogeneity in multiple domains. Intervention types ranged from differential learning to visual-motor training and standard rehabilitation protocols, with varying frequencies and durations. Settings included laboratory environments, university clinics, and sports rehabilitation centres. Outcome measures differed notably, including neuromuscular control, balance, hop tests, and neurocognitive variables. This variability underscores the methodological diversity in the application of motor learning principles following ACLR and supports the narrative synthesis approach used in this review.

Appendix D: GRADE Summary of Findings Table

Outcome	Key References	Findings Summary	Certainty of Evidence (GRADE)	Reasons for Certainty Rating	Additional Comments
Functional performance improvements (e.g., hop tests, agility drills)	Ahmadi et al. (2020); Gholami et al. (2023); Ghaderi et al. (2021)	Most studies showed improved hop performance and agility post-intervention, particularly with DL and VMT.	Moderate	Consistent findings across moderate-quality studies; some limitations in blinding and sample size.	Applicable to non-elite athletes aged 18–35 post-ACLR.
Neurocognitive enhancement (e.g., reaction time, dual-tasking)	Wohl et al. (2021); Gokeler et al. (2019); Grooms et al. (2023)	Interventions using dual-tasking and external focus improved reaction times and cognitive-motor integration.	Low	Small sample sizes and inconsistent measurement tools across studies.	Limited transferability across sports with different cognitive demands.
Psychological readiness (e.g., kinesiophobia, confidence)	Ghaderi et al. (2021); Arundale et al. (2017); Ahmadi et al. (2020)	Positive psychological outcomes (reduced kinesiophobia, improved confidence) reported in 4 studies.	Moderate	Good consistency, but limited by self-reported outcomes and lack of long-term tracking.	More robust psychological outcome measures needed in future studies.
Biomechanical improvements (e.g., postural sway, knee stability)	Gholami et al. (2023); Ahmadi et al. (2020); Wohl et al. (2021)	Better postural control and biomechanical alignment observed, especially in DL and visuo-motor training groups.	Low	Variability in methods and biomechanical tools used; small sample sizes.	Requires standardization of assessment tools across trials.
Return to play (RTP) timelines	Bodkin et al. (2021); Bartels et al. (2016); Gokeler et al. (2022)	No studies directly measured time to RTP, but inferred improvements were noted in RTP readiness.	Low	Findings were inferred, not directly measured; indirect evidence only.	Stronger evidence required via direct time-to-RTP metrics.
Reinjury prevention	Machan and Krupps (2021); Grooms et al. (2023); Onate et al. (2019)	No conclusive evidence found on reinjury reduction due to limited long-term follow-up.	Very Low	Sparse data, inconsistent reporting, and absence of long-term follow-up metrics.	Future trials needed with reinjury as a primary endpoint.

Appendix E: Ethical Waiver

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG	HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

Office of the Deputy Vice-Chancellor (Research & Innovation)

TO: Ms A Hawke
School: Therapeutic Sciences
Department: Physiotherapy
Division:
Medical School
University
E-mail: 2635540@students.wits.ac.za

CC: Supervisor: Dr N Benjamin-Damons Natalie.Benjamin-Damons@wits.ac.za
and <HREC-Medical.ResearchOffice@wits.ac.za>

FROM: Mr Iain Burns
Human Research Ethics Committee (Medical)
Tel: 011 717 1252

E-mail: Iain.Burns@wits.ac.za

DATE: 06/06/2024

REF: *R14/49*

PROTOCOL NO: W-MvN-240606-03 (This is your ethics application study reference number. Please quote this reference number in all correspondence relating to this study)

PROJECT TITLE: *The effectiveness of neuroplastic interventions on accelerating return to play in elite athletes following anterior cruciate ligament reconstruction: a systematic review*

Please find attached the Ethics Waiver Certificate for the above project. I hope it goes well and that an article in a recognized publication comes out of it. This will reflect well on your professional standing and contribute to the Government funding of the University.

MSWorks2000/Iain0007/ClearScanWaiver.wps

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG	HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

Office of the Deputy Vice-Chancellor (Research & Innovation)

06/06/2024

Ref: W-MvN-240606-03

TO WHOM IT MAY CONCERN

Waiver: This certifies that the following research does not require clearance from the Human Research Ethics Committee (Medical)

Investigator: Ms A Hawke
Student No. (if appropriate): 2635540
Staff No. (if appropriate):

Supervisor: Dr N Benjamin-Damons

School: Therapeutic Sciences
Department: Physiotherapy
Division:
Medical School
University

Project title: *The effectiveness of neuroplastic interventions on accelerating return to play in elite athletes following anterior cruciate ligament reconstruction: a systematic review*

Degree: MSc

Reason: Review of information in the public domain
No human participants will be involved in the study

Ms M van Niekerk
Co-Chairperson: Human Research Ethics Committee (Medical)

Research Office Secretariat:
Third Floor, Phillip Tobias Building, corner of St Andrews and York Roads, Parktown, Johannesburg 2193
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Website:
https://www.wits.ac.za/research/researcher-support/research-ethics/ethics-committees/

Appendix F: Turnitin Report

Review

ORIGINALITY REPORT

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SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Eduardo Fraca-Fernández, Luis Ceballos-Laita, Héctor Hernández-Lázaro, Sandra Jiménez-del-Barrio et al. "Effects of Blood Flow Restriction Training in Patients before and after Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-Analysis", Healthcare, 2024 Publication	3%
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5	Submitted to Fiji National University Student Paper	1%
6	Franso-Mari Olivier, Benita Olivier, Candice MacMillan, Sonia Briel. "Effectiveness of neuromuscular injury prevention strategies versus standard strategies on injury rates in the adolescent male playing sport: a systematic review protocol", JBI Evidence Synthesis, 2023 Publication	1%
7	Glattke, Kaycee. "Low-Intensity Blood Flow Restriction Training as a Preoperative Rehabilitative Modality to Improve Postoperative Outcomes for Anterior Cruciate Ligament Reconstruction", Arizona State University, 2022	1%

8	Culiver, Adam M.. "Impact of Anterior Cruciate Ligament Reconstruction on the Brain's Blood Oxygen Level Dependent Response During Lower Extremity Movement", The Ohio State University, 2023 Publication	1 %
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10	Paul A. Jones, Thomas Dos'Santos. "Multidirectional Speed in Sport - Research to Application", Routledge, 2023 Publication	<1 %
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12	Mandeep Singh Dhillon, Karthick Rangasamy, Rajesh Kumar Rajnish, Nirmal Raj Gopinathan. "Paediatric Anterior Cruciate Ligament (ACL) Injuries: Current Concepts Review", Indian Journal of Orthopaedics, 2022 Publication	<1 %
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14	Adam Gledhill, Dale Forsdyke. "The Psychology of Sports Injury - From Risk to Retirement", Routledge, 2021 Publication	<1 %

8	Culiver, Adam M.. "Impact of Anterior Cruciate Ligament Reconstruction on the Brain's Blood Oxygen Level Dependent Response During Lower Extremity Movement", The Ohio State University, 2023 Publication	1 %
9	Swart, Johannes Jacobus Wessel. "The Effectiveness of Exercise Interventions to Prevent Shoulder Injuries in Sport: A Systematic Review and Meta-Analysis", University of the Witwatersrand, Johannesburg (South Africa), 2025 Publication	1 %
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15	Tanya Rutherford-Owen, Mary Barros-Bailey, Roger O. Weed. "Life Care Planning and Case Management Across the Lifespan", Routledge, 2023 Publication	<1 %
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17	Carlos De la Fuente, Rony Silvestre, Eduardo Martinez-Valdes, Roberto Yañez et al. "Time course of Quadriceps thickness changes over six months post-anterior cruciate ligament reconstruction: unveiling critical impairments in vastii muscles", Cold Spring Harbor Laboratory, 2024 Publication	<1 %
18	Naik, Rujuta. "A Neurocognitive Approach to Prevent Non-Contact Anterior Cruciate Ligament Injury in Football - A Scoping Review", The University of Nottingham (United Kingdom), 2023 Publication	<1 %
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anterior cruciate ligament injury prevention programmes in sport: a scoping review", Cold Spring Harbor Laboratory, 2023
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neuromuscular injury prevention strategies on injury rates in adolescent males playing sport: a systematic review protocol", JBI Evidence Synthesis, 2024
Publication

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Appendix G: Original Protocol

Title: The effectiveness of neuroplastic interventions on accelerating return to play following anterior
cruciate ligament reconstruction: A Systematic Review Protocol

5. 1. Background and Need

1.1 Introduction

Anterior Cruciate Ligament (ACL) tears are debilitating activity-related orthopaedic injuries that have become a heavy burden for athletes and clinicians (Wohl et al., 2021; Onate et al., 2019). They are among the most common and devastating injuries for athletes because they impose significant challenges in reaching their pre-injury level of performance and often result in shortened careers for these populations (Gokeler et al., 2022(a); Gokeler et al., 2019). Machan and Krupps (2021) estimated 200 000 ACL injuries occur annually of which 75% undergo surgical reconstruction within the first year following injury (Onate et al., 2019). Despite surgery and extensive rehabilitation, these injuries are further complicated by high rates of reinjury, contralateral injury and secondary graft rupture (Grooms et al., 2023). Athletes who return to play following an ACL injury have 30 to 40 times greater risk of reinjury in comparison to those without a history of ACL injury (Grooms et al., 2017). Numerous authors have made special note of the heightened risk of reinjury to both the contralateral and ipsilateral knees in active young athletes (<20 years) after returning to sports (Beischer et al., 2020; Gokeler et al., 2022(b)). In addition to the risk of reinjury, long-term pathological sequelae seem to develop following ACL reconstruction (Wohl et al., 2021). Aberrant joint loading, osteoarthritis of the knee, meniscal tears, and osteochondral lesions are some of the prevalent complications in patients after ACLR (Gokeler et al., 2019). Roper et al., (2016) observed that the choice of graft type had minimal influence over the prevalence of early onset arthritis, suggesting that there are other pathological factors at play.

Research has found that one of the most promising ways to prevent reinjury is to delay the time from injury or reconstruction to return to play (RTP). This means that athletes undergo a lengthy period of rehabilitation following surgery and poses a great burden on clinicians. Medical insurance companies place a limit on the number of funded treatment sessions allowed after surgery. This makes full recovery for these patients nearly

impossible when the rehabilitation period requires nine to twelve months before returning to full participation in sport (Machan & Krupps, 2021). Research has shown that the average time for return to play (RTP) for these patients is as long as 11 months (Beischer et al., 2020). Although adequate time needs to be provided for the graft to mature, there needs to be a better explanation for
why time from injury matters (Gokeler et al., 2022(a)). Machan and Krupps (2021) hypothesised that the
longer the time since injury, the greater the opportunity for athletes to learn different motor strategies. The authors suggested that if this is all that time allows, rehabilitation may have the potential to accelerate the acquisition of motor learning and ultimately shorten the time to RTP.

Seventy percent of all ACL injuries are caused by non-contact mechanisms, such as landing, pivoting, cutting, and rotational movements. Literature suggests that this is predominantly the product of sensorimotor errors that result in altered neuromuscular control mechanisms (Haggerty et al., 2020). Even after surgical reconstruction, lengthy rehabilitation, and RTP, these patients continue to show altered motor control patterns, possibly because of neural inefficiency (Roper et al., 2016). This ultimately impairs motor performance and increases the risk of secondary injury when returned to chaotic sporting environments that demand higher cognition and greater task complexity than a controlled clinical environment (Wohl et al., 2021). These neural compensations appear to serve as protective functions after injury but may be underrecognized as a factor contributing to increased risk for ipsilateral or contralateral second injury and deleterious long term effects upon RTP (Grooms et al., 2023).

Within the context of ACL injuries, RTP can only be described as truly successful when the athlete is able to return to their prior level of performance while also at a reduced or reasonable risk of new injury or re- injury. The decision of when to return an athlete to their sport is a complex, multifactorial and challenging decision (Gokeler et al., 2022(b)). Researchers have constantly been trying to formulate the best battery of RTP tests to reduce the risk for secondary injuries, but there is still much controversy about which tests will most accurately detect this risk. There seems to be no correlation between passing the current RTP tests and secondary injury as these tests are failing to identify the patients who do succumb to a secondary injury (Machan & Krupps, 2021). Gokeler et al.,

(2022)(b) found that although the current RTP tests can reduce graft ruptures by up to 60%, they have been found to increase the risk of contralateral ACL injury by 235%. This substantially large degree of risk needs to lead clinicians and researchers towards determining the factors that might be contributing to this risk but which are not being captured in traditional RTP test batteries (Grooms et al., 2023). The bare minimum for RTP requires the complete recovery of isolated musculoskeletal impairments and in the case of ACL injuries, the restoration of the mechanical stability of the knee. These requirements, however, do not ensure that the athlete is ready throughout all domains of physiology affected by injury and competition demands.

The evidence of bilateral neuromuscular changes following unilateral injury is suggestive of changes to the central nervous system (CNS) (Grooms et al., 2017). Grooms et al., (2023) suggests that this phenomenon occurs because of neural compensation and that RTP tests should evaluate this by assessing the degree of neurocognitive reliance during functional performance. Neural compensation usually manifests as elevated attention towards motor tasks that an athlete may previously have done automatically (Grooms et al., 2023). While patients may still appear to be functional, excessive dependence upon neurocognition for motor skill may increase the risk of motor coordination errors.

More recently, ACL injuries are being understood as complex neurophysiological injuries, as opposed to simple musculoskeletal injuries (Gokeler et al., 2022)(b). Although surgical reconstruction of the ACL aims to restore the mechanical stability of the knee, research has shown that it is unable to restore the neurosensory function of the ligament. The ACL contains a unique and rich supply of mechanoreceptors which feed the CNS with afferent sensory information. When insults to these receptors occur during injury and surgical reconstruction, important information about joint position sense and movement is lost, bringing the brain into a neuroplastic state as a compensatory measure (Machan & Krupps, 2021).

“Neuroplasticity is a state of cortical adaptability and refers to the broad idea that the brain can adapt and change based on internal and external stimuli”(Machan & Krupps, 2021). Research suggests that neuroplasticity is a common phenomenon following ACL injuries. Because the brain is a plastic organ and changes according to the input it receives, it is evident that the loss of afferent input following ACLR is one of the main drivers behind the

neuroplastic state found in these patients (Machan & Krupps, 2021). This CNS reorganization manifests as changes in sensorimotor control, secondary to increased attention, cognition, and reliance on visual information (Wohl et al., 2021). In this state, the brain weighs sensory information based on its reliability. The theory is based on the premise that if it can reduce the uncertainty of perception, it can maintain the function and protection of the injured joint, but through maladaptive behaviour (Wohl et al., 2021). Gokeler et al., (2019) discovered that 95% of physical therapists prescribe exercises that focus the visual attention to the knee, with increased visual and cognitive resources allocated to knee position control. These exercises are visually-dominated and do not encourage reliance on sensorimotor/proprioceptive signals, leading to suboptimal neuroplastic adaptations (Onate et al., 2019; Grooms et al., 2017). Using vision to guide motor control is maladaptive for athletes expected to return to a chaotic sporting environment. This new and maladaptive demand to integrate dynamic visual information may put a limit on what neural resources the CNS can use to guide lower limb movement (Wohl et al., 2021). Haggerty et al., (2020)suggest that traditional models of rehabilitation do not focus their goals on inducing neuroplasticity or sensory reweighting to optimize neuromuscular function. This results in the failure to efficiently address movement variability, movement pattern acquisition, and long-term motor pattern retention (Machan & Krupps, 2021). Wohl et al., (2021) suggests utilizing motor learning principles to facilitate the acquisition of injury-resistant motor patterns that persist beyond clinical settings. Gokeler et al., (2019) states that “failure to comprehensively address the interaction between sensory cues and motor responses as they relate to specific sports activities of an athlete in task and environmental constraints on the field” leads to a higher risk of re-injury. By integrating motor learning principles with the goal to modify sensorimotor neural processing, there may be a way to target injury-induced neuroplastic changes that standard therapy hasn’t been able to.

Reinnervation of the disrupted mechanoreceptors in the ACL has proven unlikely, which has led researchers to embracing the principles of neuroplasticity as a means to restore neuromuscular function (Roper et al., 2016). Just as brain activation patterns can change drastically after these injuries, the evidence is prompting clinicians to open a new pathway for rehabilitation that allows the brain to respond to these activation differences through

the application of neuroplastic constructs (Onate et al., 2019). While strength training and other current methods of musculoskeletal rehabilitation are still of utmost importance, clinicians should lend their focus to creating rich rehabilitation environments that promote neuroplasticity throughout multiple areas of the brain (Gokeler et al., 2022)(b). The principles underlying motor learning encompass aspects of neuroscience, psychology and orthopaedic rehabilitation to explain how motor development and re-learning occurs after injury. Non-contact ACL injuries occur because of coordination errors in sensory, visual or motor processing and therefore need to be rehabilitated as such (Haggerty et al., 2020). Therefore, the aim of my study is to determine whether embracing the principles of neuroplasticity can shorten the RTP timeframe while simultaneously reducing the risk of re-injury. “The opportunity to supplement traditional interventions by further targeting neuroplastic, cognitive, and visual-motor capabilities is an exciting time for research and clinical practice” (Onate et al., 2019). The implementation of this knowledge in rehabilitation is a new frontier for orthopaedic care and could promise to improve patient function and outcomes, accelerate the rehabilitation process and reduce the burden of these injuries on the sporting population.

6. 1.2 Problem Statement

Within the last 10 years, a lot of research has been devoted to understanding the neurophysiological mechanisms predisposing athletes to ACL injuries and re-injury following an ACL reconstruction. Findings of this research point towards our traditional approaches of ACL rehabilitation as being one of the
contributing factors to prolonged recovery periods after surgery and a huge culprit in the risk of re-injury. The prolonged rehabilitation process, the extended time of f sport and the cost of rehabilitation following ACLR places a huge burden on the shoulders of athletes often resulting in a premature end to their careers. It appears that the traditional rehabilitation and RTP processes may not be targeting all the physiological systems required to yield better outcomes. Traditional ACLR rehabilitation models focus on pre-planned motor skills in predictable environments and are negating the attentional and environmental components that neuroplastic methods strongly encourage. Such evidence could help to explain why patients do not always regain motor skills after ACL injury as the neuroplastic capacities may not be optimally challenged in current rehabilitation (Gokeler

et al., 2019). Our approaches to rehabilitation need to shif t towards bridging the gap between the intense neurocognitive and motor control demands of sport and the clinical setting. This would require that treatment is tailored towards creating positive neuroplastic changes by utilizing interventions that target neurological factors in addition to the biomechanical techniques that are already widely addressed (Onate et al., 2019).
A vast amount of recent research has gone into trying to improve the RTP process following these injuries. These studies have tried to predict and reduce the risk of re-injury after ACLR. Very little is known; however, about whether there is any possibility of accelerating the RTP process safely to alleviate the burden of these injuries on an athlete's lifestyle and sporting career.

7. 1.3 Review Question

What is the effect of interventions that target neuroplasticity on return to play timeframe and risk of re- injury in elite athletes following anterior cruciate ligament reconstructions?

The PICO method was used to construct the review question.

The neuroplastic interventions that will be examined could include but will not be limited to: various types of motor learning, neuromuscular training, visuo-motor training, exercises targeting movement variability and neurocognitive exercises.

8. 1.4 Aim of the Study

To establish the effectiveness of therapeutic interventions that target motor learning and neuroplasticity on accelerating the return to play timeframe and reducing incidence of re-injury following anterior cruciate ligament reconstruction.

Effectiveness will be measured using a number of outcome measures often used as part of RTP batteries following ACL reconstructions.

1.4.1 Objectives of the Study

- Compare the effectiveness of therapeutic interventions that target neuroplasticity and motor learning against traditional rehabilitation in athletes after ACLR
- Establish the association between neuroplasticity, motor learning and the return to play timeframe for athletes after ACLR
- Establish the association between neuroplasticity, motor learning and the incidence of re- injury in athletes following ACLR

1.5 Significance of the Study

A large body of research has been devoted to understanding the neurophysiological mechanisms predisposing athletes to re-injury following ACLR. Numerous studies have sought methods to predict and prevent the incidence of re-injury after ACLR and have attempted to develop the correct battery of tests needed to improve the efficacy of the RTP process. Research has suggested that an increased period of time between surgery and RTP was associated with a reduction in re-injury rates, however very little is known about why this may be the case (Gokeler et al., 2022(a)). Machan & Krupps (2021) have hypothesized that a greater timeframe may allow athletes to learn different motor strategies. The purpose of this study is to explore this hypothesis and ultimately contribute to filling this gap in knowledge.

2. Methodology

2.1 Study Design

This study is a Systematic Review of Effectiveness. It will be conducted in accordance with the JBI methodology for systematic reviews of effectiveness and will follow the guidance of the JBI Manual for Evidenced Synthesis and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). This protocol is registered in PROSPERO (CRD42024558847).

2.2 Eligibility criteria

2.2.1 Participants

This review will include studies on athletes of any age, gender and ethnicity participating in contact and non-contact sports that have undergone ACL reconstruction. Of this population, only athletes that have had an ACL reconstruction as a result of a non-contact mechanism of injury will be included. Studies reporting on athletes with secondary or additional knee injuries at the time of initial injury will be excluded. Similar neuroreceptors have been found in multiple capsuloligamentous structures within the knee joint, allowing for compensation and upregulation of remaining receptors following injury to the knee (Seitz et al., 2021). This ensures that afferent sensory information is still fed to the central nervous system following knee injury in attempt to maintain proprioception. Should participants have had injuries to multiple structures within the knee, measuring effectiveness of treatment for injury to the ACL ligament alone would become difficult to monitor.

The term ‘athletes’ can be quite broad by definition. This review will use the guidance of Williams et al. (2017) to allow readers to judge suitability of the term for themselves. The authors’ opinion and recommendations are that in the absence of quantitative performance data, as commonly occurs with most team sports, competitive experience and success in highly competitive leagues should be prioritised over international representation (Williams et al., 2017). This review will provide as much detail as possible about the sporting level of all participants, however interpretation of ‘athletes’ will be left to the audience. Studies that include mixed populations, such as elite and non-elite athletes will still be included in the review, provided that the term ‘athlete’ is stipulated as a description of the participant.

2.2.2 Interventions

Studies that evaluate interventions targeting neuroplasticity for ACLR rehabilitation for any sport will be included. These programs are multi-faceted, and the following will be included but not limited to: motor learning, neuromuscular training, visuo-motor training, exercises targeting movement variability and neurocognitive exercises. All eligible studies will be included, regardless of how the program is delivered. Interventions carried out by physiotherapists, sport trainers, sports scientists, researchers, and research assistants will be included. The effectiveness of these interventions will be measured using the outcome measurement tools listed in the outcomes section below.

2.2.3 Comparator

This review will consider studies that compare neuroplastic focused interventions (as described in above section) to the traditional rehabilitation that patients would typically receive after ACL reconstructions. If the standard rehabilitation consists of elements like those in the intervention, those elements will be treated as standard strategy, and only the elements not part of their standard training will be measured for the effectiveness of reducing RTP timeframe and preventing re-injury. Studies that do not have a clear comparator group will not be included in the study.

9. 2.2.4 Outcomes

This review will consider studies that include the following outcome measures:

- Static and dynamic balance
- Functional performance tests
- Biomechanics and Sports performance tests
- Knee joint position sense
- Vertical Ground Reaction Force
- Psychological Kinesiophobia Status
- Functional knee assessments
- Patient-reported function
- Isokinetic muscle strength performance

Through inference, interpretation and application, these outcomes measures will inform the RTP timeframe as the primary outcome of interest and the risk of re-injury after successful RTP as the secondary outcome of interest.

10. 2.2.4 Types of Studies

This review will consider both experimental and quasi-experimental study designs including randomized controlled trials, non-randomized controlled trials, before and after studies and interrupted time-series studies. In addition, analytical observational studies including prospective and retrospective cohort studies, case-control studies and analytical cross-sectional studies will be considered for inclusion. This review will also consider descriptive observational study designs including case series, individual case reports and descriptive cross-sectional studies for inclusion. Studies with the predefined keywords that exist as a whole or at least in title, keywords or abstract section of the paper will be included. Papers that are duplicated within the search documents, papers that are not accessible, review papers, meta-data and papers that are not primary research papers will be excluded from the study.

11. 2.3 Search Strategy

The search strategy will aim to locate both published and unpublished studies. First an initial limited search of MEDLINE (PubMed) was undertaken to identify articles on the topic. The text words contained in the titles and abstracts of relevant articles, and the identified keywords and index terms used to describe the articles were used to develop a full search string.

A 3-step search strategy was developed with the help of an expert research librarian from Wits University. First, a preliminary test of the search string was conducted using MEDLINE (PubMed). The search strategy was piloted to refine it by removing duplicate or inadequate search terms and retesting as necessary to ensure that it was sufficiently sensitive to identify all relevant studies.
Secondly, the search strategy, including all identified keywords and index terms, will be adapted for each bibliographic database. Keywords will be searched in titles and abstracts, index terms, and, where possible, MeSH terms.

Thirdly, a search will be performed on the reference lists of the studies selected for critical appraisal to identify any additional studies to be included in the review. Theses or dissertations found in grey literature databases will be included in the review. Further, known experts could be contacted to identify any additional publications.

The following databases will be searched with the help of a librarian: Scopus; MEDLINE (Pubmed); SPORTDiscus (EBSCO); PEDro; CINAHL Complete (EBSCO); CLinicalKey, ScienceDirect (Elsevier), Health and Medical Complete (ProQuest), Cochrane Central Register of Controlled Trials (CENTRAL), and all other databases recommended by Wits Health Sciences library. Sources of unpublished studies and gray literature to be searched will include ProQuest Dissertations and Theses Global.

Databases will be searched using the following search string: ACL OR “anterior cruciate ligament” OR “anterior cruciate ligament injuries” OR “ACL injuries” OR “anterior cruciate ligament reconstruction” OR “ACL reconstruction” OR “anterior cruciate ligament repair”

OR “ACL repair” OR “anterior cruciate ligament surgery” OR “ACL surgery” OR “anterior cruciate ligament reconstruction” OR “ACL surgical reconstruction” AND “central nervous system” OR brain OR neuroscience OR neuroplasticity OR “neuroplastic processes” OR “neuronal plasticity” OR “motor control” OR “motor control/learning” OR “motor learning” OR “motor learning strategy” OR “motor learning principles” OR “principles of motor learning” OR “movement variability” OR “kinematic variability” OR “neuromuscular control” OR “sensory reweighting” AND “subsequent ACL injury” OR “subsequent anterior cruciate ligament injury” OR “second anterior cruciate ligament injury risk” OR “second ACL injury risk” OR “secondary injury” OR reinjury OR reinjuries AND rehabilitation OR “therapeutic intervention” OR “exercise therapy” OR treatment AND “return to sport” OR “return to performance” OR “return to play” AND athletes OR “elite athletes” OR “professional athletes”

Studies published from authors of specific papers will be contacted 3 times to provide missing details and clarification. Any disagreements that arise between the reviewers will be resolved through discussion or
with a third reviewer. All papers will undergo data extraction irrespective of quality, and appraisal results will be displayed in the summary table.

Only studies that are published in English and published between 2013 and 2024 will be included. After performing a preliminary search of the PubMed database it was evident that the understanding of the role that neuroplasticity plays in sports injuries is still an emerging idea and that this timeframe allows guaranteed inclusion of neuroplasticity concepts. The screenshot below shows the distribution of studies over the years, with a significant rise in relevant studies from 2013 onwards.

12. 2.4 Selection of studies

All identified citations retrieved from the database search will be collated and imported into Mendeley Reference Manager and all duplicates will be removed. Citations will then be imported into the JBI System for the Unified Management, Assessment and Review of

Information (Munn et al.,2019). Following a pilot test involving the two reviewers screening at least 3 studies, all abstracts and titles will be screened in JBI SUMARI by the two independent reviewers for assessment against the inclusion criteria for this review. Studies whose titles and abstracts are unclear, will also be included for further screening. Two independent reviewers will then conduct a detailed assessment of each full-text paper under consideration against the inclusion and exclusion criteria. Full-text articles that do not fulfil the inclusion criteria will be excluded from the study, and the reasons for the exclusion will be recorded and reported in the final systematic review. Any disputes that arise between the two reviewers at each stage of the selection process will be resolved through discussion or by bringing in a third reviewer who will make the final decision. The search results and the study inclusion process will be reported in full in the final systematic review and presented in a Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) flow diagram.

13. 2.5 Critical Appraisal

High-quality evidence is essential for clinical practice protocols and guidelines, and evidence used in systematic reviews must undergo critical appraisal to assess quality, rigor and potential biases.

A critical appraisal assessment of each of the eligible articles will be conducted by the two independent reviewers using the JBI standardized critical appraisal checklists that most appropriately matches the methodology of each study. For example, the critical appraisal tools that may be used include a checklist for quasi-experimental studies (Barker, 2024), analytical cross sectional studies (Moola, 2020), cohort studies (Moola, 2020), case report studies (Moola, 2020), case control studies (Moola, 2020), case series (Munn, 2020) and randomized controlled trials (Barker, 2023).

Where information concerning an individual study is missing or unclear, authors of specific papers will be contacted 3 times to provide missing details and clarification. A third reviewer will be used to finalize any disputes not resolved through discussion between the two independent reviewers. Any reasons for exclusion at the full-text stage will be documented in the final review. A table with a supporting narrative will be used to illustrate the results of all critical appraisals performed.

For a study to receive a positive response to a critical appraisal question, sufficient detail needs to be provided within the study for a reviewer to answer, without doubt, all dimensions of the question. For a study to receive a negative response to a critical appraisal question, sufficient detail needs to be provided
by the authors to allow a reviewer to formulate an explanation that portrays an answer contrary to the requirement of the specific question. For a study to receive an unclear response to a critical appraisal question, the reviewer should feel unclear about the answer as a result of insufficient, unclear or missing information. All studies, regardless of the results of their methodological quality, will undergo data extraction and synthesis. The quality, reliability and relevance of each study will be considered while review conclusions are being formulated. The methodological quality of each study will be considered and will contribute to the ‘weighting’ of influence that its’ results can hold, in comparison to the others.

14. 2.6 Data Extraction

The two independent reviewers will extract data from included studies using the standardized JBI SUMARI data extraction tool (Munn et al.,2019), JBI SUMARI, when possible. All data will be extracted manually without automation tools. The extracted data will be relevant to the study objectives and will be presented in several tables. The tables will include but not be limited to the following details: authors names, article names, article title, year of publication, country of study, setting and context, methodology, research design, variables and results. Special attention will be paid to the following variables in each study:

- Participants (number of participants, type and level of sport played, age, gender, ethnicity, mechanism of initial injury)
- Neuroplastic interventions (intervention type, content, dosage and frequency, who delivered the intervention)
- Traditional rehabilitation methods (intervention type, content, dosage and frequency, who delivered the intervention)
- Compliance and follow-up
- Outcomes (as listed under outcomes section)
- Critical appraisal rating

A pilot data extraction will be conducted to familiarize the two independent reviewers with the tool and to evaluate its appropriateness for this study. The pilot run will also assist with minimizing data extraction errors in the main study. Once the two reviewers are familiar with the process, relevant data will then be extracted independently. Should a dispute arise between the reviewers, a third reviewer will be used to resolve the dispute. Confounding factors reported in the included studies will also be extracted and accounted for. Where required, missing or additional data will be requested from the authors of papers. In cases where no response is obtained from an author, a reminder email will be sent 10 days after the initial email.

2.7 Data Synthesis

It is predicted that statistical pooling may not be possible and therefore the extracted data will be synthesized through a narrative analysis and not a meta-analysis. Descriptive tables, figures and graphs may be utilized to present this data.

2.7.1 Reporting of the Strength of Evidence

Since meta-analysis may not be possible the GRADE approach will not be used. The level of confidence will be derived from the critical appraisal of each study included in the review. The quality of studies will be reported as low, medium and high. This will be undertaken by two independent reviewers at the outcome level. Any disagreements that arise between the reviewers will be resolved through discussion or with a third reviewer.

Authors of papers were contacted to request missing or additional data for clarification, where required.

15. 2.8 Ethical Considerations

Since this study is a systematic review, no active human participants will be needed for the study. An ethical waiver has been applied for through the Wits Health Consortium. Please see the attached waiver in the appendices.

Any potential biases will be eliminated by strictly adhering to the inclusion and exclusion criteria. Where a dispute arises between the two independent reviewers, a third reviewer will be brought in to settle the dispute.

2.9 Impact of the Study on Clinical Practice

The expected outcome of this study is that the reviewed literature will show that interventions using neuroplastic principles to treat and rehabilitate reconstructed ACL's will be more effective in improving the various outcome measures, will accelerate the RTP process and will reduce the risk of re-injury in
comparison to traditional rehabilitation models. The implications that this may hold for clinical practice is in furthering the understanding of best rehabilitation practices for a common yet complicated injury.

16. 3. Time Frame of the Project

Research phase	**Jan-Mar**			**Apr-Jun**			**Jul-Sept**			**Oct-Dec**		
Proposal development												
Departmental protocol presentations												

School assessors submission & permission												
Ethics committee submission												
Data collection												
Data analysis												
Write-up												
Submission of publication												
Submission for examination												

4. Budget

Any funds needed for this research project will be funded by the SASP/Faculty Research Grant/personally financed. Please see the below table presenting the budget for the study.

Item	**Explanation**	**Cost**
Printing costs	Printing of thesis at the end of the project	R100
Purchasing of articles	24 hour access +- 20 articles	R400
JBI Software license	For myself & research assistant	R5000

Research Assistant	The research assistant (a Wits Masters student) will be the second reviewer for this study.	R150 per hour

17. Dissemination and Translation

The protocol and final study will be published with JBI to disseminate the study on a global level. The results will also be presented at a selected sports and rehabilitation local conference.

This study has the potential to impact the world of sport and sports medicine at a global level. It could assist with the development or revision of rehabilitation protocols following anterior cruciate ligament reconstructions to enhance and optimize athlete recovery. It could also inform the management of other musculoskeletal injuries by applying concepts learned in this study.

18. References

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6. Appendices

6.1 Search Strategy

6.2 Search result on PROSPERO

6.3 JBI Critical Appraisal Tools

19. JBI CRITICAL APPRAISAL CHECKLIST FOR CASE REPORTS

Reviewer_____ Date

Author_____Year____ Record Number

	Yes	No	Unclear	Not applicable
1. Were patient's demographic characteristics clearly described?	□	□	□	□
2. Was the patient's history clearly described and presented as a timeline?	□	□	□	□
3. Was the current clinical condition of the patient on presentation clearly described?	□	□	□	□
4. Were diagnostic tests or assessment methods and the results clearly described?	□	□	□	□
5. Was the intervention(s) or treatment procedure(s) clearly described?	□	□	□	□
6. Was the post-intervention clinical condition clearly described?	□	□	□	□
7. Were adverse events (harms) or unanticipated events identified and described?	□	□	□	□
8. Does the case report provide takeaway lessons?	□	□	□	□

Overall appraisal: Include □ Exclude □ Seek further info □

Comments (Including reason for exclusion)

20. JBI CRITICAL APPRAISAL CHECKLIST FOR CASE CONTROL STUDIES

Reviewer_____ Date

Author_____Year____ Record Number

1. Were the groups comparable other than the presence of disease in cases or the absence of disease in controls?
2. Were cases and controls matched appropriately?
3. Were the same criteria used for identification of cases and controls?
4. Was exposure measured in a standard, valid and reliable way?
5. Was exposure measured in the same way for cases and controls?
6. Were confounding factors identified?
7. Were strategies to deal with confounding factors stated?
8. Were outcomes assessed in a standard, valid and reliable way for cases and controls?
9. Was the exposure period of interest long enough to be meaningful?
10. Was appropriate statistical analysis used?

Yes No Unclear Not applicable

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Overall appraisal: Include □ Exclude □ Seek further info □

Comments (Including reason for exclusion)

JBI Critical Appraisal Checklist for Case Series

Reviewer_____ Date

Author_____Year____ Record Number

	Yes	No	Unclear	Not applicable
	□	□	□	□
Were there clear criteria for inclusion in the case series?				
Was the condition measured in a standard, reliable way for all participants included in the case series?	□	□	□	□
Were valid methods used for identification of the condition for all participants included in the case series?	□	□	□	□
Did the case series have consecutive inclusion of participants?	□	□	□	□
	□	□	□	□
Did the case series have complete inclusion of participants?				
Was there clear reporting of the demographics of the participants in the study?	□	□	□	□
Was there clear reporting of clinical information of the participants?	□	□	□	□
Were the outcomes or follow up results of cases clearly reported?	□	□	□	□

Was there clear reporting of the presenting site(s)/clinic(s) demographic information?	□	□	□	□
Was statistical analysis appropriate?	□	□	□	□

Overall appraisal: Include □ Exclude □ Seek further info □

Comments (Including reason for exclusion)

21. JBI CRITICAL APPRAISAL CHECKLIST FOR ANALYTICAL CROSS SECTIONAL STUDIES

Reviewer_____Date_____ Author_____Year____ Record Number

	Yes	No	Unclear	Not applicable
1. Were the criteria for inclusion in the sample clearly defined?	□	□	□	□
2. Were the study subjects and the setting described in detail?	□	□	□	□
3. Was the exposure measured in a valid and reliable way?	□	□	□	□
4. Were objective, standard criteria used for measurement of the condition?	□	□	□	□
5. Were confounding factors identified?	□	□	□	□
6. Were strategies to deal with confounding factors stated?	□	□	□	□

7. Were the outcomes measured in a valid and reliable way?	□	□	□	□
8. Was appropriate statistical analysis used?	□	□	□	□

Overall appraisal: Include □ Exclude □ Seek further info □

Comments (Including reason for exclusion)

22. JBI CRITICAL APPRAISAL CHECKLIST FOR QUASI-EXPERIMENTAL STUDIES

Reviewer_____Date

Author_____Year____ Record Number

	Yes	No	Unclear	Not applicable
1. Is it clear in the study what is the 'cause' and what is the 'effect' (i.e. there is no confusion about which variable comes first)?	□	□	□	□
2. Were the participants included in any comparisons similar?	□	□	□	□
3. Were the participants included in any comparisons receiving similar treatment/care, other than the exposure or intervention of interest?	□	□	□	□
4. Was there a control group?	□	□	□	□

5. Were there multiple measurements of the outcome both pre and post the intervention/exposure?	□	□	□	□
6. Was follow up complete and if not, were differences between groups in terms of their follow up adequately described and analyzed?	□	□	□	□
7. Were the outcomes of participants included in any comparisons measured in the same way?	□	□	□	□
8. Were outcomes measured in a reliable way?	□	□	□	□
9. Was appropriate statistical analysis used?	□	□	□	□

Overall appraisal: Include □ Exclude □ Seek further info □

Comments (Including reason for exclusion)

23. JBI CRITICAL APPRAISAL CHECKLIST FOR COHORT STUDIES

	Yes	No	Unclear	Not applicable
1. Were the two groups similar and recruited from the same population?	☐	☐	☐	☐
2. Were the exposures measured similarly to assign people to both exposed and unexposed groups?	☐	☐	☐	☐
3. Was the exposure measured in a valid and reliable way?	☐	☐	☐	☐
4. Were confounding factors identified?	☐	☐	☐	☐
5. Were strategies to deal with confounding factors stated?	☐	☐	☐	☐
6. Were the groups/participants free of the outcome at the start of the study (or at the moment of exposure)?	☐	☐	☐	☐
7. Were the outcomes measured in a valid and reliable way?	☐	☐	☐	☐
8. Was the follow up time reported and sufficient to be long enough for outcomes to occur?	☐	☐	☐	☐
9. Was follow up complete, and if not, were the reasons to loss to follow up described and explored?	☐	☐	☐	☐
10. Were strategies to address incomplete follow up utilized?	☐	☐	☐	☐
11. Was appropriate statistical analysis used?	☐	☐	☐	☐

Reviewer_____Date_____ Author_____Year___ Record Number

Overall appraisal: Include □ Exclude □ Seek further info □

Comments (Including reason for exclusion)

24. JBI CRITICAL APPRAISAL CHECKLIST FOR RANDOMIZED CONTROLLED TRIALS

Reviewer_____ Date

Author_____Year___ Record Number

	Yes	No	Unclear	NA
9. Was true randomization used for assignment of participants to treatment groups?	□	□	□	□
10. Was allocation to treatment groups concealed?	□	□	□	□
11. Were treatment groups similar at the baseline?	□	□	□	□
12. Were participants blind to treatment assignment?	□	□	□	□
13. Were those delivering treatment blind to treatment assignment?	□	□	□	□
14. Were outcomes assessors blind to treatment assignment?	□	□	□	□
15. Were treatment groups treated identically other than the intervention of interest?	□	□	□	□
16. Was follow up complete and if not, were differences between groups in terms of their follow up adequately described and analyzed?	□	□	□	□
17. Were participants analyzed in the groups to which they were randomized?	□	□	□	□
18. Were outcomes measured in the same way for treatment groups?	□	□	□	□
19. Were outcomes measured in a reliable way?	□	□	□	□
20. Was appropriate statistical analysis used?	□	□	□	□
21. Was the trial design appropriate, and any deviations from the standard RCT design (individual randomization, parallel groups) accounted for in the conduct and analysis of the trial?	□	□	□	□