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Review

Neurocognitive Changes and Advanced Testing Approaches in Anterior Cruciate Ligament Injuries: Review

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Abstract

Anterior cruciate ligament (ACL) injuries are one of the most common injuries experienced by athletes. ACL injuries not only have effects on the musculoskeletal system, but can also lead to significant changes in neurocognitive processes. This study examines 46 studies published between 2018 and 2024. Keywords such as sensorimotor dysfunction, visual reliance, return to play/sports, neuroscience, and neural plasticity/neuroplasticity were used in searches conducted on PubMed, Web of Science, Scopus, and Google Scholar. The review provides an in-depth analysis under the headings of ACL injuries, neurocognitive abilities, neural compensations, visual reliance, and the development of return-to-sport (RTS) tests. ACL injuries lead to neurocognitive changes that affect athletes' motor control, attention, and executive functions. Impairments in these functions can result in coordination deficits and increased injury risk. Visual reliance emerges as a compensatory mechanism used by the central nervous system (CNS) to address proprioceptive deficits following ACL injuries. However, heightened visual-cognitive demands may prolong decision-making times and reduce movement efficiency in athletes. Neural compensation processes involve neuroplasticity and adaptive changes to recover lost sensorimotor functions. During this process, the CNS requires increased brain activation to maintain motor control. Moreover, advanced RTS tests developed post-ACL injury aim to evaluate not only biomechanical performance but also neurocognitive functions. In conclusion, investigating neurocognitive changes following ACL injuries offers novel insights into rehabilitation strategies. Neurocognitive-enhanced RTS tests and rehabilitation programs to account for these changes can better support athletes' functional and cognitive recovery.

Keywords: Anterior cruciate ligament injuries, brain plasticity, return to sports, sensorimotor dysfunction.

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Anterior cruciate ligament (ACL) injuries are among the most common injuries encountered by athletes and typically occur during high-intensity activities.[1] These injuries not only adversely affect functional performance but also necessitate an extensive physical rehabilitation process.[2] However, the impact of ACL injuries extends beyond the musculoskeletal system, as they can also lead to significant alterations in neurocognitive processes. Athletes are often required to operate in dynamic and unpredictable environments, which challenge their sensitivity to environmental cues, motor planning abilities, and attentional focus.[3] These demands are particularly

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pronounced in team sports, where such factors can contribute to an increased risk of injury. Neurocognitive changes following ACL injury are thought to play a crucial role in understanding the mechanisms of injury and informing rehabilitation strategies.

The relationship between ACL injury and neurocognitive abilities is a key factor influencing an athlete's capacity to adapt to environmental cues. Neurocognitive components such as executive functions, working memory, and cognitive flexibility can significantly affect both performance and injury risk.[4–6] Following ACL injury, impairments in cognitive abilities, particularly attention and memory, can compromise motor control, potentially increasing the likelihood of subsequent injuries. Moreover, deficits in neurocognitive functioning can adversely affect an athlete's ability to coordinate movements effectively.[7]

Post-injury neural compensations are associated with the body's adaptations to compensate for the loss of sensory inputs. This process aims to restore motor control by enhancing the integration of visual and proprioceptive sensory information.[8] However, these neuroplastic changes may introduce new challenges in an athlete's movements and decision-making processes. For instance, a reliance on visual inputs post-ACL injury can disrupt the balance between mechanical and cognitive functionality.[9,10]

Finally, the development of return-to-sport (RTS) tests requires an integrated approach that considers not only biomechanical performance but also neurocognitive functions. Assessing an athlete's cognitive abilities – such as attention, memory, and motor planning – enables the evaluation of both physical and cognitive recovery. In this context, improved RTS tests can yield results more representative of real-game performance, promoting a safer and more comprehensive recovery process during the RTS phase.[11]

Materials and Methods

This study was conducted as part of the "FTR6024 Musculoskeletal Physiotherapy and Rehabilitation" course within the Doctoral Program of the Department of Physiotherapy and Rehabilitation at the Graduate School of Education, Bahçeşehir University, under the guidance of Dr. Berkay Eren Pehlivanoğlu. In our study, a systematic search was performed across the PubMed, Web of Science, Scopus, and Google Scholar databases. The search was limited to studies published between 2018 and 2024 and utilized the following keywords: ACL injury, sensorimotor dysfunction, visual reliance, return to play/sports, neuroscience, and neural plasticity/neuroplasticity. The inclusion criteria encompassed meta-analyses, systematic reviews, narrative reviews, and randomized controlled clinical trials relevant to the scope of this research. Following the screening process, a total of 46 studies were included in this review based on their relevance and alignment with the study's objectives.

Results

ACL Injury

ACL injuries are the most common type of injury encountered by athletes throughout their careers.[1] Approximately 70% of ACL injuries occur during non-contact situations, such as sudden changes in direction after landing on one leg.[2] These injuries are often associated with an increased risk of meniscal tears, osteochondral lesions, and early-onset knee osteoarthritis.[3] Non-contact ACL injuries are recognized in the literature as a type of injury primarily caused by sensorimotor errors, including weakened neuromuscular control and increased knee valgus.[4]

Researchers emphasize that the mechanisms of ACL injuries should not be analyzed solely within a biomechanical framework. Instead, they recommend considering the context of the sport, including the athlete's actions and those of their opponents. Particularly in team sports, athletes perform under time pressure in rapidly changing and unpredictable environments.[5] These conditions necessitate cognitive functions such as perceiving movements of both themselves and their opponents, as well as making appropriate action decisions accordingly. Deficiencies in perceptual or attentional processes can lead to coordination errors and risky knee movements, thereby increasing the likelihood of ACL injuries.[6]

ACL Injury and Neurocognitive Ability

Neurocognition refers to the understanding of cognitive functions in relation to the neural mechanisms in the brain. Higher-level neurocognitive functions, commonly known as executive functions, enable individuals to adapt to environmental cues by coordinating cognitive, emotional, and motor processes.[7] These functions consist of components such as working memory, inhibitory control, and cognitive flexibility. Traditionally considered distinct, cognitive constructs are now recognized as overlapping, spanning from fundamental sensory processes to executive control mechanisms.[6]

Sporting activities require continuous environmental monitoring, filtering out irrelevant information, and executing complex motor programs simultaneously. While performing dynamic movements, athletes process various cognitive stimuli such as reacting to opponents, making decisions, and formulating strategies.[5] These cognitive abilities significantly influence neuromuscular control, biomechanical movement patterns, and injury risk.[5,7] Deficits in the ability to shift or sustain attention on a stimulus can lead to a loss of spatial awareness and impaired motor control.[6,8] Neuropsychological attributes such as situational awareness, motor planning, and coordination directly impact joint stiffness and injury prevention strategies. Studies have indicated an increased risk of non-contact ACL injuries in athletes with poor cognitive abilities. In addition, reduced reaction time has been linked to a higher risk of lower extremity injuries.[7]

In the mechanism of non-contact ACL injury, dynamic knee valgus during landing after a single-leg jump is the primary contributing factor.[1] However, in addition to increased knee valgus, diminished neurocognitive functions and altered neuromuscular characteristics are highlighted as potential risk factors, particularly in young female athletes.[5,8] Video analyses have revealed that during competitions, injured basketball players often shift their focus between the hoop, the opponent, and the ball. This divided attention reduces the athlete's focus on their own movements and limits the time available to correct actions, potentially triggering ACL injuries.[7,9]

Neural Compensations Following ACL Injury

Mechanical instability, pain, and subsequent kinesiophobia, along with muscle strength deficits, are among the challenges athletes face after an ACL injury.[1] These prolonged issues lead to somatosensory impairments and compensatory mechanisms,[8,10] which trigger central nervous system (CNS) adaptations.[11,12] Sensorimotor neuroplasticity following ACL injury begins with the abrupt loss of afferent feedback.[13,14] This loss, combined with pain and inflammatory responses, induces fundamental alterations in somatosensory feedback.[12] Impairments in gamma motor neuron function and reflex activity reflect changes in motor output, impacting the ability to maintain neuromuscular integrity.[14] The CNS compensates for diminished sensory feedback by employing additional mechanisms, such as visual feedback.[11] This process involves spinal and supraspinal pathways, leading to bilateral motor control and proprioceptive changes. Increased brain activation has been observed post-ACL injury, resulting in the recruitment of additional brain regions to support motor control.[9]

Neuroplasticity associated with ACL injury encompasses cross-modal neural activity involving changes in the parietal and occipital lobes, where visual and proprioceptive sensory information is processed.[15] This post-injury neuroplasticity alters motor output, joint stabilization mechanisms, and activity in regions associated with cognitive functions such as decision-making, executive function, and attentional focus within the frontal lobe.[11,15] Enhanced cognitive and cross-modal neural activities following ACL injury may provide sufficient joint stabilization, a critical factor during the RTS phase.[9]

Considering the neurocognitive changes observed in the CNS, it becomes evident that ACL injury should not be regarded merely as a musculoskeletal injury. Instead, its broader impact on sensory-motor integration and neuroplastic adaptations highlights its multifaceted nature.

Visual Reliance Following ACL Injury

The sensorimotor system plays a critical role in movement planning, execution, and maintaining postural control. The integration of somatosensory and visual information is essential for detecting movement deviations and adjusting motor responses. As movement complexity increases, sensorimotor demands also rise.[16] Following an ACL tear, the CNS may rely more heavily on alternative sensory inputs such as visual feedback and spatial awareness.[12] Figure 1 shows the relationship between the sensorimotor system and the motor control mechanism.

In individuals with ACL insufficiency, increased activation has been observed in brain regions such as the posterior inferior temporal gyrus (visual processing), pre-supplementary motor area (motor planning), and secondary somatosensory area (pain and sensory processing).[7,8] Studies have demonstrated greater neural activity during the processing of identical visual inputs in injured athletes compared to uninjured counterparts, supporting this hypothesis.[12,17] To compensate for altered somatosensory processing, athletes require greater reliance on visual input to maintain their performance levels.[9]

Visual cognition involves interpreting, integrating, and making sense of visual input. It also integrates spatial functions such as object recognition and depth perception.[16] Athletes who have sustained an ACL injury experience increased cognitive loads to process augmented visual input associated with their sports, often resulting in slowed reaction times.[18] A failure to balance cognitive and biomechanical functions adequately, coupled with delayed reaction times, renders these athletes more susceptible to secondary injuries.[13]

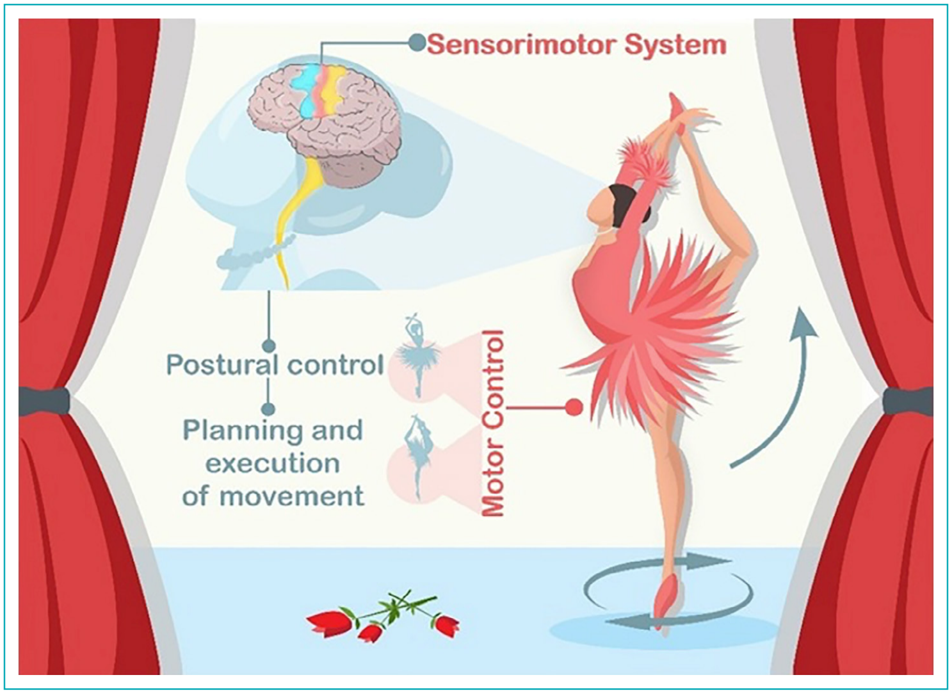

Figure 1. Relationship between sensorimotor system and motor control mechanism.[16]

These findings emphasize the need for rehabilitation programs to address the heightened visual reliance following ACL injuries, focusing on restoring the balance between visual and somatosensory systems to enhance motor control and reduce the risk of re-injury.

Developing RTS Tests Following ACL Injury

RTS criteria for athletes recovering from ACL injuries often focus on evaluating musculoskeletal functionality, such as agility, strength, and jumping performance. Test batteries that assess single-leg landing biomechanics and performance are commonly utilized as benchmarks for RTS.[19] However, reliance solely on tests that evaluate jumping performance and musculoskeletal systems often leads to suboptimal outcomes, such as failure to regain pre-injury performance levels and a heightened risk of secondary ACL injuries.[20] Athletic performance and injury risk are intricately linked to a complex integration of physical, cognitive, and visuospatial abilities. Therefore, incorporating visual and neurocognitive functional tests into the RTS criteria is of critical importance.[21] Neurocognitive-enhanced RTS tests should include components that assess both reactive movements and pre-planned agility maneuvers.

To evaluate the neurocognitive adaptations that occur after ACL injuries, many clinical test procedures can be modified. For example, adding a simple timed light sensor to traditional jump tests can measure visually mediated reaction times, offering a neurocognitive perspective on the athlete's readiness. Dual-task challenges that target cross-modal neural changes – requiring athletes to respond to specific cues while maintaining motor performance and stabilization – can further assess cognitive, proprioceptive, and visual capabilities.[15,21] Enhanced neurocognitive jump tests, incorporating stimuli such as lights, colors, or numbers, can evaluate not only movement initiation but also the cognitive and visual reliance during jumps.[9,15] In addition to integrating neurocognitive tasks into jump tests, agility tests measuring reaction time, linear speed, and sudden directional changes can also benefit from dual-task components. These modifications can provide insights into the compensatory strategies developed post-injury.[22] As an example test, Figure 2 shows the lateral slide test with light targets.

The addition of neurocognitive dual-task components to performance tests must minimize reliance on pre-planned agility maneuvers and reactive movements.[23] During sports competitions, athletes must respond to unpredictable conditions with automatic, spontaneous actions. Therefore, RTS assessments should simulate real-world scenarios encountered during competitive play. Incorporating neurocognitive components – such as executive function, attention, and memory – can create a more comprehensive evaluation framework, ensuring that athletes are better prepared for the demands of their sport.[23]

Figure 2. Lateral slide test with light targets. The lateral slide test involves an athlete shuffling laterally between four Blazepods, targeting the blue light while avoiding hopping or running. The athlete catches a soccer ball thrown to the target light, taps the light, and then tosses the ball back while moving to the next light. The goal is to tap as many lights as possible in 30 seconds, with total taps and average reaction time recorded and scored.[23]

Discussion

In this study, we focused on the impact of ACL injuries on neurocognitive changes and the significance of these changes in advanced test approaches. Specifically, we examined the effects of ACL injuries on motor control, neuromotor function, visuomotor integration, and the neurocognitive challenges encountered during the RTS process. This discussion highlights the nature of neurocognitive changes post-ACL injury and how these changes can be integrated into clinical assessments and rehabilitation strategies, supported by findings from various academic studies.

After ACL injuries, the CNS recruits additional brain regions to support motor control processes. Chaput et al.[9] demonstrated that the CNS allocates increased resources to maintain motor control, resulting in heightened brain activation following ACL injuries. This suggests that athletes rely more heavily on cognitive resources to coordinate movements and experience significant neurocognitive changes while regaining motor control. Similarly, Sherman et al.[13] found that individuals with ACL reconstruction (ACLR) exhibit greater motor planning and response inhibition compared to healthy controls. By examining electrocortical activities, the study revealed how neurocognitive adaptations influence motor planning and response selection, emphasizing their critical role in the RTS process.[13] Armitano-Lago et al.[24] also observed reduced performance in challenging postural tasks among individuals with ACLR compared to healthy controls, highlighting changes in motor function. These findings underline the need to consider brain activity alterations aimed at improving motor control when designing rehabilitation strategies.

The brain may develop new motor strategies post-injury to manage challenges, a phenomenon known as neurocognitive compensations. Criss et al.[25] reported increased activation in various brain regions, particularly the fronto-insular-temporal and sensorimotor areas, during a hip-knee movement paradigm in individuals with ACLR. These connections suggest that individuals rely on additional brain resources for visuospatial cognitive processes and motor control.[25] Similarly, Zarzycki et al.[26] identified variations in intracortical facilitation effects between limbs in ACLR patients and found that increased motor cortex inhibition could impair quadriceps strength. These findings underscore the importance of understanding neural adaptations in post-injury recovery. Lehmann et al.[17] observed enhanced functional connectivity in somatosensory and visual regions during postural control tasks in ACLR patients, suggesting the importance of neural compensation mechanisms during rehabilitation. These mechanisms are closely tied to physiological parameters such as muscle strength and postural stability.[17]

One notable finding is the increased reliance on visual inputs after ACL injuries. Miko et al.[27] (2021) showed that ACLR individuals experience greater instability during visual-motor dual tasks, impacting postural stability. This highlights the need for rehabilitation programs that address not only physical recovery but also visual-cognitive training.[27] Similarly, Wein et al.[28] demonstrated that ACLR patients become more dependent on visual feedback for postural control, emphasizing its critical role in rehabilitation.

ACLR individuals often exhibit reduced performance in tasks requiring visuomotor integration during RTS testing. Simon et al.[21] reported lower performance on neurocognitive jump tests compared to traditional tests, highlighting the importance of incorporating neurocognitive components into RTS criteria. Sports often demand rapid decision-making and increased motor control, reinforcing the need for neurocognitive testing in RTS assessments.[21] Brinkman et al.[29] evaluated the reliability of visuomotor reaction time and emphasized its importance as a critical parameter reflecting athletic performance. Similarly, Farraye et al. [30] validated a novel visuocognitive medial side-hop test, demonstrating its effectiveness in measuring both physical and cognitive loads during RTS.[30] These findings suggest that integrating neurocognitive tests into RTS assessments provides a more comprehensive evaluation than traditional tests. Simulating dual-task scenarios or situations requiring rapid decision-making may offer a more reliable means of assessing athletes' readiness to return to sport.

Limitations

A limitation of our study is that it is not a systematic review, which has led to a less comprehensive evaluation of the literature. However, the fact that this is a traditional review has allowed for greater attention to the subject matter. This review will provide valuable insights for future clinical studies.

Conclusion

The significance of neurocognitive changes and advanced test approaches in the RTS process following ACL injuries is unquestionable. High brain activation, visual input dependency, and changes in motor control processes are key factors shaping rehabilitation and testing approaches. It is clear that combining neurocognitive tests with traditional assessments will provide more reliable and functional RTS tests. These tests are expected to be an important tool for accelerating the return to sport and optimizing athlete performance.

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