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REVIEW ARTICLE

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Disrupted sensorimotor control after ACL injury: from mechanoreceptor degeneration to neuroplasticity-oriented rehabilitation

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ABSTRACT

Background: Anterior cruciate ligament (ACL) injury is one of the most common sports-related injuries, often resulting in not only mechanical instability but also long-term proprioceptive dysfunction. The ACL is richly innervated with mechanoreceptors that contribute to sensorimotor control. Injury-induced degeneration of these receptors leads to disrupted afferent signaling and maladaptive central nervous system (CNS) responses, which can compromise functional recovery and increase the risk of reinjury.

Objective: This review aims to summarize current knowledge on ACL-associated proprioception, including mechanoreceptor anatomy, injury-induced changes in neural signaling, and advances in evaluation and rehabilitation techniques. Emphasis is placed on the integration of peripheral and central mechanisms and their implications for clinical interventions.

Content: We detail the types and distribution of mechanoreceptors within the ACL and describe how their disruption alters joint position sense and kinesthesia. We further explore CNS neuroplasticity, such as cortical reorganization and bilateral sensorimotor changes. Traditional and emerging methods for proprioceptive assessment are critically evaluated. Finally, we discuss surgical and rehabilitative strategies—including remnant-preserving reconstruction, neuromuscular training, and neurofeedback—that target proprioceptive recovery through neuroplastic adaptation.

Conclusion: Restoration of proprioceptive integrity following ACL injury requires a multifaceted approach that addresses both peripheral mechanoreceptor preservation and central sensorimotor reorganization. Future research should focus on standardized assessments, long-term neurophysiological monitoring, and the integration of sensor-based technologies to support individualized, neuroplasticity-driven rehabilitation strategies.

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Introduction

Anterior cruciate ligament (ACL) injuries are among the most prevalent and debilitating musculoskeletal injuries, particularly affecting young, active populations [1,2]. While the biomechanical consequences of ACL rupture—such as joint instability and altered kinematics—are well recognized [3], increasing evidence has underscored the pivotal role of proprioceptive impairment in functional deterioration and recurrent injury [4]. Proprioception, a composite sensory modality involving joint position sense, kinesthesia, and neuromuscular reflexes, is largely mediated by mechanoreceptors embedded within the ACL [5]. These receptors form a critical feedback loop with the central nervous system (CNS), regulating joint stability, movement precision, and motor control [6].

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Recent advancements in neurophysiology, histology, and imaging have expanded our understanding of proprioceptive degradation following ACL trauma, highlighting both peripheral receptor damage and central neural reorganization [6–9]. Moreover, the clinical relevance of proprioceptive deficits has prompted a paradigm shift in ACL treatment [4,5,10]—from purely structural repair to functional restoration—including novel strategies in graft selection, remnant preservation, early intervention, and sensorimotor rehabilitation. Several recent reviews have refined the current understanding of proprioceptive rehabilitation after ACL reconstruction. Most have confirmed that proprioception-oriented training improves passive joint position sense, single-leg hop performance, and postural balance, but its impact on muscle strength and range of motion remains limited [11,12]. Other analyses have compared emerging approaches such as virtual-reality-based training, which may enhance balance control through greater central engagement [13]. From a surgical perspective, remnant-preserving reconstruction has been linked to improved proprioceptive and stability outcomes, though long-term evidence remains inconclusive [14]. Building on these findings, the present review differs from previous work by integrating peripheral mechanoreceptor biology, central neuroplastic adaptations, and clinical rehabilitation practice.

This review comprehensively synthesizes current evidence on ACL proprioception, covering anatomical substrates, post-injury alterations, evaluation techniques, and therapeutic interventions. By critically examining recent literature and identifying key knowledge gaps, we propose an integrative framework for optimizing proprioceptive recovery and improving long-term functional outcomes after ACL injury. Although extensive research has addressed biomechanical instability following ACL rupture, the contribution of proprioceptive deterioration and its neurophysiological consequences has not been systematically consolidated. Here, we integrate emerging evidence on peripheral mechanoreceptor degeneration and central nervous system neuroplasticity to explain persistent sensorimotor dysfunction, and we highlight how bidirectional interactions between neural adaptations and rehabilitation interventions can inform neuroplasticity-oriented, precision rehabilitation that goes beyond conventional strength-based approaches.

Mechanoreceptors in the ACL

Emerging research highlights the ACL as a sensory hub, endowed with mechanoreceptors intricately woven into its structure, primarily concentrated at its tibial and femoral junctures beneath the synovial membrane [7,10]. These mechanoreceptors, constituting about 1% to 2.5% of the ligament's total volume, are pivotal in the proprioceptive matrix of the knee joint [6,8,9,15,16]. Recent histological studies have identified four principal types of mechanoreceptors within the ACL—Ruffini corpuscles (Type I), Pacinian corpuscles (Type II), Golgi tendon organs (Type III), and free nerve endings (Type IV) [6,7]—each specialized in relaying nuanced information regarding joint dynamics, such as static position, motion direction, and mechanical stress (Figure 1). This rich sensory input is essential for the fine-tuning of neuromuscular responses, underpinning joint stability and movement precision.

Ruffini corpuscles are fusiform, low-threshold, and slowly adapting receptors situated superficially within the ligament. They detect static joint position and intra-articular pressure changes, thereby contributing to sustained postural control and the perception of joint motion direction [6,8]. Pacinian corpuscles are ovoid, fast-adapting receptors embedded in the deeper layers of the ligament; while inactive in static conditions, they rapidly respond to sudden joint movements and acceleration, providing feedback about dynamic changes in joint position [6,10]. Golgi tendon organs are high-threshold, slowly adapting receptors localized near ligament insertions. They are activated primarily at the extremes of joint motion or under high tensile stress, functioning to prevent excessive joint rotation or hyperextension [9,17]. Free nerve endings, which are irregularly distributed throughout the ligament, act as polymodal nociceptors responsible for pain perception, inflammatory responses, and local vasoregulation [5,15].

Table 1 summarizes the main types and functions of mechanoreceptors found in the ACL. These mechanoreceptors constitute an intricate afferent network that continuously transmits information about joint angle, position, mechanical tension, and acceleration to the central nervous system. Following integration with visual and vestibular inputs, this proprioceptive feedback enables the fine-tuning of neuromuscular responses necessary to maintain dynamic knee stability and coordinated movement [6,18,19].

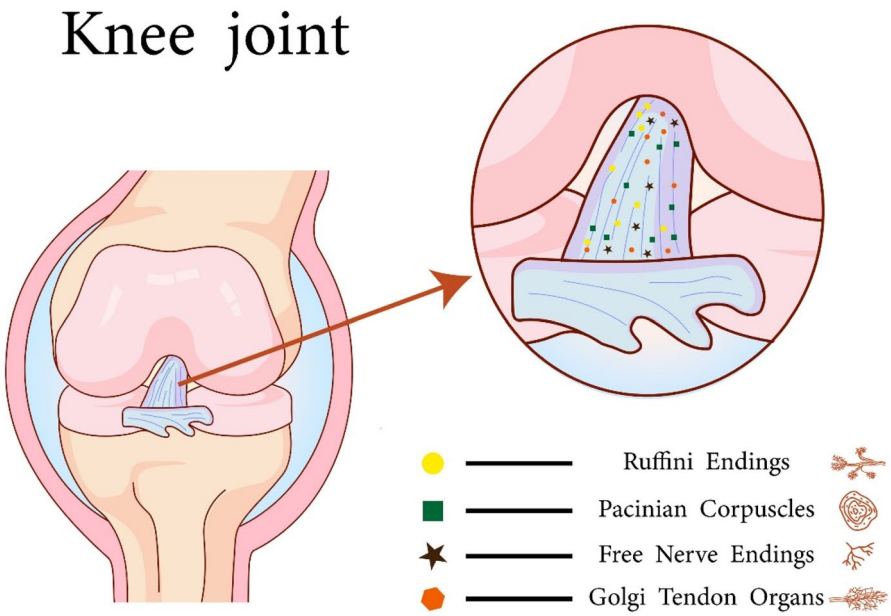


Figure 1. Classification and morphology of mechanoreceptors in the anterior cruciate ligament (ACL). This schematic diagram illustrates the four major types of mechanoreceptors identified within and around the ACL: Ruffini endings (type I), Pacinian corpuscles (type II), Golgi tendon organs (type III), and free nerve endings (type IV). Each receptor type plays a distinct role in proprioception, responding to different mechanical stimuli such as tension, pressure, vibration, and nociception. These mechanoreceptors are distributed variably along the ligament, contributing to afferent signaling necessary for joint position sense and reflexive motor control.

Table 1. Types and functions of mechanoreceptors in the ACL.

Type	Morphology	Functional role
Ruffini corpuscles (Type I)	Fusiform, located superficially	Low-threshold, slow-adapting; detect static position and intra-articular pressure [6,8]
Pacinian corpuscles (Type II)	Ovoid, found deeper in the ligament	Low-threshold, fast-adapting; respond to sudden movements and acceleration [6,10]
Golgi tendon organs (Type III)	Fusiform near ligament insertions	High-threshold; respond to extreme joint movements and tension [9,17]
Free nerve endings (Type IV)	Irregular, widely distributed	Nociceptors; detect pain and participate in inflammation [5,15]

Evolution and function of ACL proprioception

The conceptualization of proprioception has evolved since its inception by Sir Charles Sherrington, who envisaged it as the body's intrinsic awareness of limb positioning and movement through space [20]. This concept has evolved, now broadly recognized not just as joint position sense but also incorporating kinesthetic awareness—subconscious perceptions of movement and spatial orientation. This expanded understanding aligns with recent neurophysiological research suggesting proprioception as a composite sensory modality, integrating signals from mechanoreceptors within the ACL to facilitate joint stability and dynamic neuromuscular adjustments [21]. This complex interplay is critical for executing precise movements, safeguarding the knee from injury, and orchestrating rehabilitation strategies post-ACL reconstruction. Some scholars view proprioception as merely joint position sense [22,23], others argue it encompasses both joint position and movement senses, with movement sense as a subset of proprioception [24–26]. This broader interpretation aligns with Bastian's description, emphasizing the intertwined nature of position and movement senses in daily activities. Thus, proprioception can be considered synonymous with 'movement sense' [27].

Proprioception refers to the sensation generated by muscles, tendons, joints, and other motion-related organs in different states (movement or stillness), also known as deep sensation [28,29]. Proprioception mainly has three functions: 1) static perception of joint position; 2) perception of joint movement (perception of joint movement or acceleration); 3) reflex response and regulation of muscle activity. The first

two reflect the afferent capabilities of proprioception, while the latter reflects the efferent capabilities of proprioception [28,30].

The proprioception of the knee joint protects the joint from excessive movement, maintains joint stability, and coordinates joint movement [31–33]. Within the proprioceptive structure of the knee joint, the ACL plays a crucial role. ACL injury leads to changes in knee joint stability not only due to biomechanical changes caused by ligament deficiency but also due to changes in proprioception after ligament injury [34]. Therefore, the proprioceptive function of the anterior cruciate ligament is essential for maintaining the stability of the knee joint.

Changes in proprioception following ACL injury

The precise mechanisms through which ACL injuries precipitate alterations in proprioception are yet to be fully elucidated. The ACL injury is known to induce significant alterations in knee proprioception, primarily due to the damage to the mechanoreceptors embedded within the ligament and subsequent impairment in the proprioceptive signal transmission pathways [35,36]. These alterations reduce the accuracy of proprioceptive feedback and neuromuscular control, diminishing quadriceps activity, compromising knee stability and strength, and increasing the risk of reinjury [37]. Early-stage experimental research conducted by Zhang et al. in a cynomolgus monkey model demonstrated a significant decline in joint position sense following unilateral ACL injury, which progressively worsened over time, suggesting bilateral proprioceptive adaptation and long-term sensory impairment [38]. Complementary findings by Gao et al. reveal a reduction in the number and volume of mechanoreceptors in the ACL remnant as time post-injury progresses [17], highlighting the time-sensitive nature of proprioceptive deterioration.

Moreover, the reduction in proprioceptive input is thought to trigger neuroplastic changes within the CNS, as a compensatory mechanism to the loss of incoming signals [39]. This adaptability of the CNS, while beneficial in some respects, may also lead to a diminished capacity for processing and integrating complex proprioceptive information. Research has shown that individuals with ACL injuries exhibit changes in cortical activity related to movement and sensation, suggesting that the brain undergoes a form of 'reprogramming' in response to altered proprioceptive input [40]. This CNS adaptation potentially recalibrates the brain's perception of knee joint proprioception, further influencing joint stability and function.

Additionally, it has been confirmed that unilateral ACL injury not only affects the injured side but may also lead to proprioceptive changes in the contralateral, uninjured limb [5,41,42]. This bilateral impact suggests that proprioceptive deficits post-ACL injury are not confined to the local site of injury but have a more systemic influence, affecting posture balance, joint stability, and muscle strength of the non-injured limb as well [43,44]. Table 2 outlines the characteristic proprioceptive changes observed after ACL injury.

Measurement methods of proprioception following ACL injury

Due to the diversity in the content and form of proprioception, it cannot be directly assessed. This has led to a lack of standardized, universally accepted clinical methods for measuring proprioception following ACL injuries. Recent studies have identified several commonly used methods for assessing proprioception, which can be categorized into four main types.

Active and passive joint position reproduction techniques

The active and passive joint position reproduction techniques (JPR) are the most commonly used methods to measure joint position sense (JPS) [48,49]. These techniques assess the individual's ability to

Table 2. Proprioceptive changes following ACL injury.

Injury stage	Neural changes	Impact on proprioception
Acute phase	Receptor disruption, loss of afferent signals	Decreased joint position sense and neuromuscular control [17,38]
Chronic phase	Progressive receptor degeneration	Impaired postural balance and contralateral deficits [41,42]
Postoperative phase	Partial reinnervation possible with intervention	Dependent on graft type, surgical timing, and rehabilitation [45–47]

perceive joint position by examining the active or passive replication of predetermined flexion and extension angles of the knee [50,51]. The difference between the replicated angle and the preset angle is calculated to gauge the knee joint's positional awareness [18,27,52]. Several variables can be manipulated during this test to create various JPS testing protocols [30,53], such as the method of angle reproduction (active or passive), direction of movement (extension or flexion), limb demonstrated (ipsilateral or contralateral), body posture (lying, sitting, or standing), measurement range (starting and target angle), load bearing status (weighted or unweighted), testing instruments (such as goniometers or dynamometers), and the method of result measurement (absolute error, constant error, variable error). Recent investigations have demonstrated moderate-to-excellent test–retest reliability of knee JPR, with intraclass correlation coefficients (ICCs) ranging approximately from 0.60 to 0.95, depending on task posture, active or passive mode, and device standardization [51,54].

Passive motion perception threshold measurement

The threshold to detection of passive motion (TDPM) is another common method used to measure the capacity of proprioception to perceive joint dynamics without other sensory mechanisms. This technique involves slowly and continuously moving the knee joint passively, typically starting from a stationary position, with visual, auditory, and tactile senses masked. The test progresses with the knee joint flexing and extending at a low angular velocity until the participant perceives the start of the movement. The angles at the onset of movement and when the movement is detected by the participant are measured to quantify and compare the differences, thereby assessing the accuracy of knee joint proprioception [27,28,55]. Reported test–retest reliability for knee TDPM varies across studies, with ICCs reported approximately between 0.52 and 0.70 in healthy cohorts, and evidence in ACL-injured populations remains inconsistent; reliability depends on the test protocol, starting angle, and measurement setup [56].

Postural sway test

Some researchers suggest that instability following ACL rupture typically occurs under load-bearing conditions [57,58] The postural sway test provides a representative assessment of proprioceptive capability in such conditions. In this method, participants stand on a force plate with eyes closed (to control for visual influence) and arms crossed over the chest. Changes in the center of pressure (COP) and its distribution displayed on the screen reflect anterior–posterior and medial–lateral sway. The variability index of COP displacement quantifies the magnitude of sway, thereby reflecting postural stability under load-bearing conditions [58,59]. This method has demonstrated moderate-to-high test–retest reliability in ACL-deficient or reconstructed cohorts, with ICCs approximately spanning 0.60–0.95, contingent on stance condition and the specific COP parameter assessed [57,60–62].

Somatosensory evoked potentials (SEPs) measurement

Following mechanical or electrical stimulation to the knee joint, changes in surface electromyography and/or cortical potentials are measured, providing a comprehensive evaluation of the neuromuscular circuitry. Although a few studies use implanted electrodes for selective stimulation of the ACL, most results are obtained through external perturbations. The sensory signals acquired depend on the integrated input from skin, joint capsules, ligaments, tendons, muscle receptors, and even visual-vestibular systems. The latency and amplitude of the evoked potentials provide indirect insights into proprioception. This method is advantageous when comparing the neuromuscular excitation patterns of patients and healthy individuals during functional exercises [28,53]. However, sensory thresholds can vary individually, often influenced by factors such as gender, age, psychological states, and external environment. While SEPs are valuable for assessing central sensory processing, published data on test–retest reliability in ACL-injured or reconstructed populations are extremely limited; thus, specific ICC values for this context cannot currently be confidently stated.

When conducting these proprioceptive tests, reliance is on the sum of information transmitted to the CNS. Therefore, interference from additional proprioceptive information should be minimized. Furthermore,

many studies use the uninjured contralateral limb as a control, but proprioceptive decline in the injured limb may also affect the uninjured side. Thus, comparisons with control groups (uninjured groups) may not always be accurate.

Among the commonly used proprioceptive assessments following ACL injury, each test provides distinct insights into sensorimotor function. Joint position reproduction and passive motion threshold tests quantify the static and dynamic components of joint position sense, postural sway testing evaluates functional balance under load-bearing conditions, and somatosensory evoked potentials characterize central sensory processing mechanisms. Based on current evidence, postural sway testing demonstrates the greatest functional relevance for evaluating proprioception during daily and sport-specific activities. Nevertheless, a multimodal approach that integrates several assessment methods is recommended to achieve a comprehensive evaluation of proprioceptive function.

The impact of ACL reconstruction on proprioception

Following ACL injuries, particularly complete ruptures or severe damage, arthroscopic reconstruction has become the mainstream treatment approach. Research has demonstrated that, compared to repair surgeries, reconstruction offers higher joint stability, lower joint laxity, and reduced failure rates [63]. Ligament reconstruction can restore the mechanical functions of the damaged ligament, and extensive studies have confirmed that it can also improve the proprioceptive function of the knee joint to a certain extent [53,64].

Effects of graft selection on proprioceptive recovery

Currently, three primary types of grafts are utilized in ACL reconstruction surgery: autografts, allografts, and synthetic ligaments. Ozenci et al. conducted a comparative study including 80 participants divided into four groups (autograft, allograft, ACL-deficient, and healthy controls; mean age ≈ 29 years), and found no significant difference in proprioceptive recovery between autograft (bone–patellar tendon–bone) and allograft groups following reconstruction [45]. Young et al. analyzed 10 patients (7 men, 3 women; mean 33 years) undergoing revision or second-look arthroscopy after ACL reconstruction (5 autograft and 5 allograft recipients). Histological examination showed that the concentration of neurofilament protein–positive mechanoreceptors was markedly reduced in both graft types compared to native ACL tissue, with no significant difference between autografts and allografts [65]. Angoules et al. performed a prospective trial involving 40 patients (34 men, 6 women; mean 31 years) who underwent ACL reconstruction using either hamstring tendon or bone–patellar tendon–bone autografts. Proprioception, assessed by joint position sense (JPS) and threshold to detection of passive motion (TTDPM) at 3, 6, and 12 months postoperatively, demonstrated that knee proprioception returned to normal by 6 months, with no significant difference between the two graft types at any time point [66]. Xu et al. conducted a randomized controlled trial of 40 patients (31 men, 9 women; aged 17–51 years) comparing hamstring autografts and synthetic LARS ligaments. Using passive–passive JPS testing at 45° and 75° of knee flexion, they found no significant difference in proprioceptive recovery between the two groups at 3 or 12 months after surgery [46]. These findings suggest that the type of graft may have a minimal impact on the recovery of proprioception post-ACL reconstruction. However, harvesting the semitendinosus and gracilis tendons for autografts could potentially damage the tendons' proprioceptors, thereby affecting knee joint proprioception.

Timing of surgery

The optimal timing for ACL reconstruction surgery remains controversial. Sha et al. studied quantitative changes in mechanoreceptors in the tibial remnant and found that the number of mechanoreceptors did not significantly decline post-ACL rupture, and residual mechanoreceptors could be preserved for up to one year [67]. Adachi et al. also found no relationship between the time from injury to surgery and the number of residual mechanoreceptors [68]. However, Dhillon and Denti suggested that the longer the duration from ACL injury to surgery, the fewer the number of residual mechanoreceptors [69,70]. Zhang

et al. found that ACL remnants collected within three months post-injury had higher healing potential, and early surgical intervention (within 90 days post-injury) could lead to better clinical outcomes [71].

Recent literature increasingly supports early ACL reconstruction surgery for optimal outcomes. Lee et al. quantitatively assessed proprioception and postural stability in patients with acute ACL tears (within 3 months post-injury) versus chronic tears (over 3 months post-injury). The study revealed that longer delays from injury to surgery resulted in significantly poorer proprioception and stability in the affected knees [47]. Furthermore, immunohistochemical analyses have shown that the timing of surgery critically affects the quantity of mechanoreceptors in the ACL stump, with delays potentially leading to a reduction in their number [72]. This evidence underscores the importance of timely surgical intervention to preserve proprioceptive function and enhance postoperative knee stability.

Remnant-preserving ACL reconstruction

There is some debate about whether to preserve the ruptured ACL remnant during reconstruction surgery. Traditional methods involve removing the tibial remnant to facilitate arthroscopic visibility and surgical manipulation. In recent years, preserving the remnant has shown potential benefits in enhancing vascular reconstruction, cellular proliferation, and promoting vascular ingrowth of the graft. The ACL remnant contains various types of mechanoreceptors that can better preserve and restore proprioceptive functions. Increasingly, scholars are focusing on the benefits of preserving the intraoperative remnant [67,68]. Takahashi et al. conducted an animal study comparing remnant-preserved and remnant-removed ACL reconstruction in goats, finding that remnant preservation promoted cell proliferation, vascular reconstruction, reduced anterior translation, and enhanced proprioceptive function regeneration [73]. Lee et al. confirmed in a retrospective human clinical study that remnant preservation during ACL reconstruction surgery better restored proprioceptive functions than remnant removal, suggesting enhanced reinnervation and mechanoreceptor maintenance [74]. Similarly, conducted a prospective clinical study in 46 patients and reported that preserving at least one-third of the native ligament length during surgery led to significantly improved proprioceptive recovery compared with complete remnant resection [75]. Mahmoud Ahmed et al. included 109 patients with intact ACL remnants, where 56 underwent remnant-preserving surgery and 53 had remnant removal; the results showed that remnant-preserving reconstruction produced functional outcomes similar to remnant removal and better restored proprioception [76]. Igdir et al. included 44 patients with ACL tears, half of whom underwent remnant-preserving surgery, finding better proprioceptive recovery and muscle strength in the remnant-preserved group [77]. Although remnant preservation during ACL reconstruction may increase the risk of Cyclops syndrome, recent studies by Webster et al. and Bierke et al. have shown that remnant preservation does not increase the incidence of Cyclops syndrome compared to traditional ACL reconstruction methods [78,79]. These findings align with the latest systematic review by Chen et al. which demonstrated that remnant-preserving ACL reconstruction offers measurable improvements in knee stability and proprioceptive recovery without elevating complication rates, although the overall quality and consistency of evidence remain limited across studies [14].

The impact of ACL primary repair on proprioception

Primary repair of the ACL appears to significantly influence proprioception recovery compared to traditional reconstruction methods. Studies have shown that primary ACL repair can preserve proprioceptive function due to the retention of the natural ACL tissue, which contains mechanoreceptors crucial for joint position sense [80,81]. A cohort study indicated that patients who underwent primary ACL repair exhibited significantly better proprioception at various angles of knee flexion compared to those who had ACL reconstruction [80,82]. Another study assessing proprioceptive function post-repair found that patients who underwent ACL repair with additional augmentation had proprioceptive function almost identical to their healthy contralateral knees and significantly better than those who had ACL reconstruction using semitendinosus muscle tendons [83]. Supporting these findings, Müller et al. conducted a study comparing primary ACL repair with augmentation to ACL reconstruction [84]. Their study suggested that techniques preserving the native ACL offer potential benefits in maintaining proprioceptive

function, muscle strength, and overall functional outcomes. Histological and clinical evidence indicates that primary ACL repair can preserve vascularity and proprioceptors within the native ligament, facilitating better proprioceptive recovery compared with reconstruction [47,72,85]. Furthermore, early surgical intervention—preferably within three months of injury—has been associated with greater mechanoreceptor preservation and improved proprioceptive and functional outcomes [5,86].

The evidence collectively underscores the importance of timely surgical intervention and the potential benefits of primary ACL repair in selected patient groups. Primary repair not only preserves native ACL tissue but also provides better short-term proprioceptive outcomes, which are essential for knee stability and function [47,80]. These findings suggest a paradigm shift towards considering primary repair as a viable option for specific ACL injuries, particularly those with proximal femoral avulsion tears and suitable stump quality. Further research is warranted to explore the long-term proprioceptive and functional outcomes of primary ACL repair compared to reconstruction.

Proprioception recovery training after ACL injury

ACL injuries significantly impact knee joint function, and the long-term success of ACL reconstruction surgery largely depends on consistent post-operative rehabilitation. Research indicates that systematic, regular rehabilitation exercises can effectively alleviate pain, nourish joint cartilage, reduce knee contracture and scar formation, decrease the incidence of post-operative patellofemoral pain, lessen muscle atrophy, enhance functional mobility, and maintain knee stability, which is as crucial as the surgery itself [87]. As understanding of ACL proprioception deepens, its critical role in knee joint function is increasingly recognized. However, ACL injuries result in decreased proprioception, leading to reduced joint stability. Traditional rehabilitation has primarily focused on restoring joint mobility and muscle strength, with a lack of targeted training for proprioception and neuromuscular control [88]. Currently, there is no clear, standardized protocol for restoring proprioceptive function after an ACL injury [89]. Table 3 presents key intervention strategies aimed at enhancing ACL proprioception along with their proposed neurophysiological mechanisms.

Proprioception training

Proprioception training is designed to enhance balance, flexibility, and agility. During training, the CNS regulates proprioceptive signals from the limbs, trunk, and neck, as well as sensory signals from the vestibular and visual systems, to maintain joint stability and improve motor functions [90]. The primary training methods include closed kinetic chain exercises, balance and control training on balance boards, joint stability training, perturbation training, visual feedback motion programs, curvature envelopment exercises for the feet and knees, lateral bounding drills, and running drills in various directions and speeds, including reverse lay-ups and 'S' runs. Recent systematic reviews have further clarified the clinical value of proprioceptive-focused and virtual-reality–assisted rehabilitation after ACL reconstruction. Huang et al. reported that proprioception-oriented training significantly improves passive joint position sense, single-leg hop performance, and postural balance, whereas its effect on muscle strength and range of motion remains limited [11]. Likewise, Shamsi Majelan et al. found that virtual-reality-based balance training yields comparable or even superior gains in postural stability compared with conventional proprioceptive exercises, highlighting the potential role of immersive feedback in central sensorimotor engagement [13]. These findings emphasize that proprioceptive and VR-assisted interventions

Table 3. Intervention strategies for enhancing ACL proprioception and underlying mechanisms.

Intervention	Mechanism	Observed outcome
Neuromuscular training	Stimulates afferent pathways and CNS plasticity	Improves proprioception, reduces risk of reinjury [91,93]
Proprioceptive training	Enhances joint awareness *via* sensory feedback integration	Enhances postural control and dynamic stability [90,96]
Remnant-preserving surgery	Retains native mechanoreceptors	Better proprioceptive recovery compared to full removal [73,74]
Primary ACL repair	Maintains original ligament and neural structures	Superior proprioception in short-term compared to reconstruction [80,85]

complement rather than replace traditional strength and mobility programs, and they reinforce the need for individualized, multi-modal rehabilitation strategies.

Neuromuscular proprioceptive enhancement training

Neuromuscular training addresses some shortcomings of traditional rehabilitation. Studies by Ghaderi et al. [91]. have demonstrated that neuromuscular training can enhance proprioception in the knee after ACL reconstruction. Defined as training that enhances unconscious motor responses by stimulating sensory input and central mechanisms responsible for dynamic joint control, it aims to improve lower limb biomechanics, neuromuscular control, and dynamic stability in the affected area, reducing the risk of athletic injuries and enhancing overall athletic performance [92,93]. Neuromuscular training includes strength training, balance exercises, rapid expansion and contraction exercises, proximal control training, and agility training. The training progresses from static to dynamic control and is generally divided into six phases: early post-operative recovery (1–2 weeks), walking phase (2–4 weeks), balance and dynamic knee stability training phase (5–10 weeks), strength training phase (11–18 weeks), running and jumping training phase (19–24 weeks), and progressive training and agility phase (25–48 weeks). Although neuromuscular training has advantages in promoting isokinetic strength and recovery of movement, starting it early can increase the risk of joint swelling. Therefore, the optimal intensity and timing for early neuromuscular training still require further research [94].

Vibration training

Vibration training is an innovative method of somatosensory stimulation that can partly restore proprioception. During vibration training, the patient stands on a continuously vibrating platform that transmits vibration waves from the soles of the feet upwards, activating mechanoreceptors in and around the ACL, thereby enhancing the knee's perception of position and movement. This method also strengthens lower limb muscle power and enhances the neuromuscular feedback mechanism, thereby improving the dynamic stability of the knee joint. Kruse et al. reviewed 29 Level I–II clinical trials on postoperative ACL rehabilitation and found that vibration-based neuromuscular training may confer modest improvements in proprioception, although the supporting evidence remains limited [95]. They emphasized that vibration training should be regarded as an adjunct rather than a substitute for standard strengthening and functional rehabilitation [95]. Maghbouli et al. in a meta-analysis, demonstrated the effectiveness of vibration training in rehabilitating patients with ACL reconstructions, showing significant benefits in strengthening the hamstring and quadriceps muscles, especially when the local muscle vibration frequency exceeds 100 Hz [96].

Mechanisms linking AMI and proprioceptive impairment

Arthrogenic muscle inhibition (AMI) is a condition characterized by the reflexive inhibition of muscles surrounding a joint following injury or surgery, preventing full voluntary muscle activation [97]. This phenomenon is commonly observed after ACL injuries and significantly impacts rehabilitation and functional recovery [98–100]. The relationship between AMI and proprioceptive impairment is characterized by a complex feedback loop where disrupted sensory input from joint mechanoreceptors leads to reflexive muscle inhibition [101] (Figure 2). This inhibition, in turn, exacerbates proprioceptive deficits, creating a challenging cycle that impacts joint stability and functional recovery (Figure 2). Effective rehabilitation strategies must address both aspects to ensure comprehensive recovery post-ACL injury or surgery [102].

Disruption of sensory feedback loops

AMI primarily arises from altered sensory feedback from the injured joint [101,103]. Proprioceptive impairment involves a diminished ability to sense joint position and movement, disrupting the afferent signals

from mechanoreceptors in the joint. These mechanoreceptors are crucial for providing the CNS with information about joint status, which is necessary for appropriate muscle activation [46].

Reflexive inhibition

Proprioceptive deficits lead to changes in the reflex pathways that control muscle activity [104]. Specifically, the altered input from the joint's mechanoreceptors affects spinal reflexes, leading to the inhibition of alpha motor neurons that innervate the muscles around the joint [97]. This reflexive inhibition is a protective mechanism to prevent further damage but unfortunately results in muscle weakness and atrophy [46].

Joint stability and neuromuscular control

Proper proprioceptive function is essential for joint stability and dynamic neuromuscular control. When proprioception is impaired, the body's ability to stabilize the joint through coordinated muscle contractions is compromised [105]. This lack of stability can exacerbate AMI, as the muscles are less able to respond effectively to joint movements, leading to further inhibition and weakness [5].

Impact on rehabilitation

The interplay between AMI and proprioceptive impairment complicates rehabilitation efforts. Effective rehabilitation requires re-establishing both muscle strength and proprioceptive function. Techniques such as neuromuscular training, proprioceptive exercises, and modalities that enhance sensory feedback (e.g. vibration therapy) are critical in addressing both AMI and proprioceptive deficits to restore normal joint

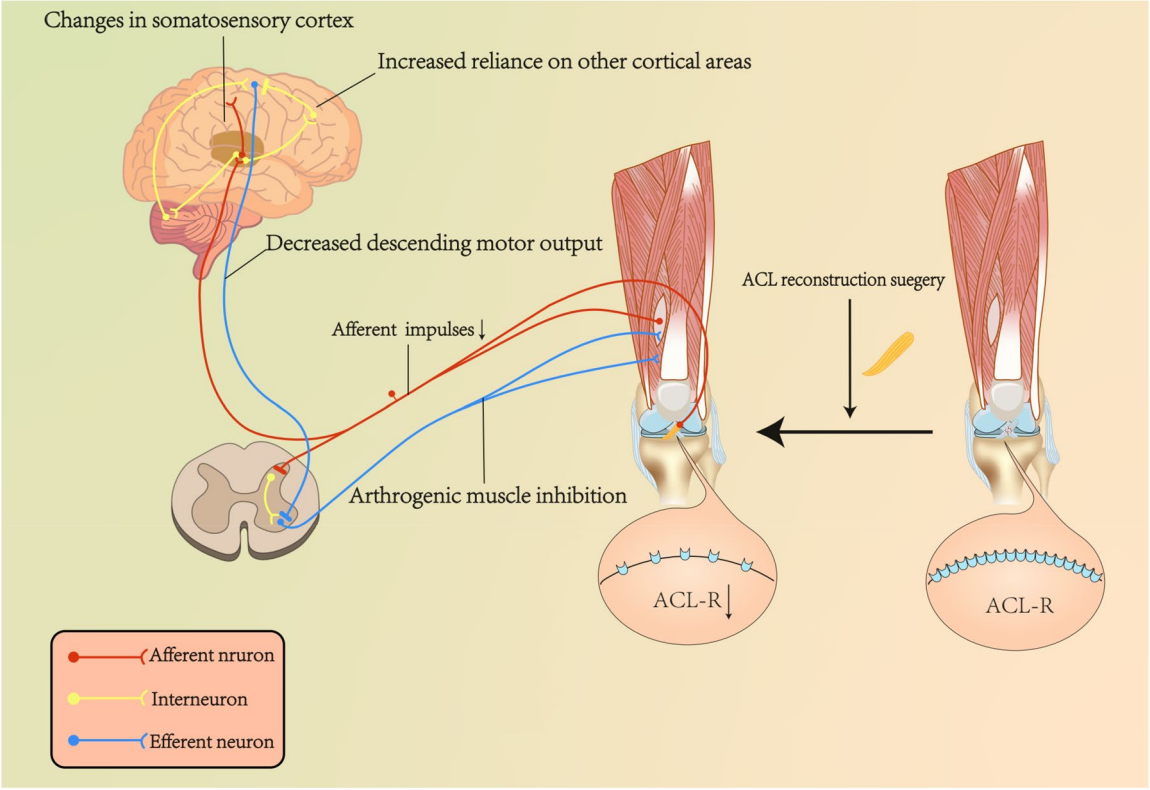


Figure 2. Neurophysiological mechanisms linking proprioceptive impairment and AMI following ACL injury. This diagram illustrates the central mechanisms by which proprioceptive deficits following ACL injury contribute to AMI. Damage to mechanoreceptors reduces afferent input, leading to maladaptive cortical reorganization—including altered somatosensory and motor cortex activation—and reduced descending motor output. These neuroplastic changes impair quadriceps activation and functional motor control, thereby reinforcing the cycle of sensorimotor dysfunction.

function [5]. Recent studies have demonstrated the impact of proprioceptive training on mitigating AMI [106]. For instance, proprioception-oriented exercises such as closed-chain weight-shift tasks, perturbation training, and balance-board exercises have been shown to enhance joint position sense and neuromuscular activation by improving afferent feedback and postural control [107–109]. In addition, joint-repositioning or angle-reproduction drills directly target position-sense accuracy and contribute to improved sensorimotor function following ACL injury [110]. Furthermore, interventions that preserve or restore mechanoreceptor function, such as remnant-preserving ACL reconstruction, have been associated with better proprioceptive outcomes and reduced AMI [5].

Neural measurements of neuromuscular function after ACL injury

Accumulating electromyography (EMG) evidence indicates altered quadriceps–hamstrings activation patterns after ACL injury and reconstruction, characterized by diminished quadriceps drive, compensatory hamstrings co-activation, and task-specific asymmetries that may persist even beyond return to sport [111,112]. Recent syntheses have broadly confirmed these activation patterns across gait, landing, and hopping paradigms, though differences in experimental protocols and EMG normalization methods remain substantial [113,114].

Reflex-based electrophysiological measures offer additional insight into both spinal and supraspinal contributions to arthrogenic muscle inhibition (AMI) [115]. Suppression of the quadriceps Hoffmann reflex (H-reflex) and reductions in the H:M ratio are frequently reported after ACL injury/ACL reconstruction, consistent with heightened presynaptic inhibition at the spinal level; related indices such as the V-wave further suggest impaired efferent drive [115]. Longitudinal and cross-sectional studies also describe altered corticospinal excitability and intracortical inhibition using transcranial magnetic stimulation (TMS) in ACL reconstruction cohorts, aligning with the persistence of activation failure despite strength rehabilitation [116].

Collectively, EMG and reflex-based assessments help quantify multi-level neurophysiological adaptations that extend beyond mechanical instability alone. Integrating these neural measures with proprioceptive and functional tests may refine longitudinal monitoring of recovery trajectories and enable more personalized interventions aimed at mitigating AMI and improving neuromuscular control [117]. Future work combining EMG, reflex indices, and imaging could help delineate the relative contribution of spinal and cortical mechanisms in long-term motor adaptation.

Limitations

Current evidence on ACL-related proprioception remains constrained by several methodological issues. Proprioceptive assessments vary widely in testing protocols and outcome measures, which limits comparability across studies. Many mechanoreceptor and neuroplasticity findings are based on small observational cohorts or animal work, reducing their direct clinical applicability. In addition, few longitudinal studies have examined how peripheral receptor changes relate to central nervous system adaptations over time. Rehabilitation approaches designed to target proprioception also differ substantially in timing, intensity, and exercise content, making it difficult to determine the most effective strategy. Finally, objective tools capable of reliably capturing proprioceptive function in clinical settings are still lacking. These factors should be considered when interpreting the current literature and designing future research.

Conclusion

Proprioception plays an essential role in maintaining dynamic stability and functional integrity of the knee joint, and its disruption following ACL injury represents a critical challenge in modern orthopaedics and sports medicine. As this review highlights, ACL injuries lead to both peripheral mechanoreceptor degeneration and central neuromuscular adaptations, collectively impairing motor coordination and increasing the risk of reinjury. Despite advances in surgical reconstruction and rehabilitative protocols, the restoration of proprioceptive function remains suboptimal in many patients. Emerging strategies—such as remnant-preserving techniques, early surgical intervention, neuromuscular training, and

proprioceptive biofeedback—have shown promise but lack standardization and robust comparative data. Furthermore, the development of objective, reliable proprioception assessment tools is urgently needed to evaluate treatment efficacy and personalize interventions. Looking forward, future research should focus on longitudinal studies integrating histological, neurophysiological, and clinical endpoints. The incorporation of wearable sensors, machine learning, and neurorehabilitation technologies may further refine proprioceptive diagnostics and therapeutics. Ultimately, restoring ACL proprioception requires a multidisciplinary, patient-specific approach that bridges molecular science, clinical practice, and rehabilitative innovation.

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Authors contributions

CRediT: **Zelong Lee**: Conceptualization, Data curation, Formal analysis, Software, Resources, Writing – original draft, Writing – review & editing; **Ying Zhang**: Conceptualization, Data curation, Formal analysis, Resources, Writing – original draft, Writing – review & editing; **Peng Wang**: Conceptualization, Data curation, Formal analysis, Software, Writing – original draft; **Zhenming Kan**: Formal analysis, Resources, Writing – review & editing; **Peng Wu**: Resources, Writing – review & editing; **Yirui Han**: Methodology, Resources; **Weiliang Zhong**: Conceptualization, Project administration, Supervision, Writing – review & editing.

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Data availability statement

No data were generated in this work. All data discussed in the manuscript are derived from previously published studies, which are cited in the reference list.

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