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Permanent knee sensorimotor system changes following ACL injury and surgery

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Abstract The cruciate ligaments are components of the knee capsuloligamentous system providing vital neurosensory and biomechanical function. Since most historical primary ACL repair attempts were unsuccessful, reconstruction has become the preferred surgery. However, an increased understanding of the efficacy of lesion-site scaffolding, innovative suturing methods and materials, and evolving use of biological healing mediators such as platelet-rich plasma and stem cells has prompted reconsideration of what was once believed to be impossible. A growing number of in vivo animal studies and prospective clinical studies are providing increasing support for this intervention. The significance of ACL repair rather than reconstruction is that it more likely preserves the native neurosensory system, entheses, and ACL footprints. Tissue preservation combined with restored biomechanical function increases the likelihood for premorbid neuromuscular control system and dynamic knee stability recovery. This recovery should increase the potential for more patients to safely return to sports at their desired intensity and frequency. This current concepts paper revisits cruciate ligament neurosensory and neurovascular anatomy from the perspective of knee capsuloligamentous system function. Peripheral and central nerve pathways and central cortical representation mapping are also discussed. Surgical restoration of a more physiologically sound knee joint may be essential to solving the osteoarthritis dilemma. Innovative rehabilitative strategies and outcome measurement methodologies using more holistic and clinically relevant measurements that closely link biomechanical and neurosensory characteristics of physiological ACL function are discussed. Greater consideration of task-specific patient physical function and psychobehavioral links should better delineate the true efficacy of all ACL surgical and non-surgical interventions.

Level of evidence IV.

Keywords Proprioception · Neuroanatomy · Repair biology · Neuromuscular control · Therapeutic exercise

Introduction

The anterior cruciate ligament (ACL) and posterior cruciate ligament (PCL) function with the collateral ligaments [1–6] and meniscocapsular tissue in close synchrony with natural joint arthrology as part of a knee capsuloligamentous (CL) system. The ACL and PCL exist in the intercondylar space helping control knee motion at six degrees of freedom [7, 8]. The cruciate ligaments control tibial rotation relative to the femur in subtle balance with CL tissues, menisci, collateral ligaments [9], condylar geometry, and joint surface contact. This system provides non-contractile joint stability, and through mechanoreceptors embedded in collagen CL matrices, transmits neurosensory information to the spinal cord and brain for precise neuromuscular responses [10–13].

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Lesions to the ACL are common [14] and remain puzzling [15, 16]. Following ACL injury, surgery has traditionally focused on reconstruction [16, 17]. Although this practice has displayed reasonable efficacy, long-term patient outcomes are often lacking in terms of neuromuscular control, dynamic knee stability, return to sports success, and the prevention of early knee osteoarthritis (OA) [16, 18–22]. More natural knee biomechanics can be restored with an anatomical double-bundle ACL reconstruction than with a non-anatomical, single trans-tibial tunnel approach [23–29]. Current ACL reconstruction practices, however, are better at restoring biomechanical than neurosensory knee function.

A growing emphasis is being placed on primary ACL repair or remnant-preserving reconstruction methods [30, 31]. Remnant tissue may enhance reconstructed or repaired ACL re-vascularization, stability, and proprioception [32–35]. Restoration of non-impaired neurosensory signals to the brain sensory cortex may facilitate the motor planning centre to more effectively regulate neuromuscular function [36–38]. Associated with this lies the potential to more effectively restore balanced hip, knee and ankle neuromuscular contributions to composite lower extremity extensor moments, primarily through more normalized quadriceps femoris function [39, 40].

What historically was considered either an ineffective procedure [17], or an exclusive intervention for paediatric clients post-insertion avulsion [41] is now being used to treat athletically active patients of widely varying ages with acute ACL lesions [31, 41–44]. The complete ACL insertional remnant debridement that enables precise graft placement, and then drilling through the entheses for reconstruction, creates a structure that differs greatly from the natural ligament. Solely focusing on ACL biomechanics during surgery may also contribute to an under appreciation for concomitant CL injuries and neurosensory impairments to synergistic tissues [9, 45, 46]. Healing that culminates in residual knee laxity, and/or poorly organized, weakened, or lesser quality collagen fibre type or orientation may be directly related to impaired mechanoreceptor function.

Limited evidence suggests that ACL reconstruction and rehabilitation effectively restores neurosensory or neuromuscular function to premorbid levels [47, 48]. Associated with this, knee OA rates remain high [19, 21], and less than optimal outcomes exist for patients who desire to participate in intense athletic activities [16, 18, 39, 49, 50]. To date, a more mechanocentric ACL reconstruction rationale has taken precedence over attempting to re-establish normal ACL neurosensory or neuromuscular functions. This current concepts paper revisits cruciate ligament neurosensory and neurovascular anatomy from the perspective of knee CL system function. Peripheral and central afferent–efferent pathways are described based on contemporary brain function mapping. The tissue preservation provided by native ACL repair may have greater neuromuscular control system recovery potential and, therefore, dynamic knee stability restoration that more closely matches premorbid levels than ACL reconstruction [51]. This potential increases the likelihood that athletically active patients would be better able to safely return to intense, high-frequency athletic movements while avoiding knee re-injury, contralateral knee injury, or early-onset knee OA.

Native cruciate ligament anatomy

The level of scrutiny given to the dimensions, orientation, and location of the native ACL or graft has led to its being described over time as a strand, a bundle, more than one bundle, or a ribbon [24, 34, 52–55]. This attention has largely focused on optimizing ACL biomechanical function through more precise insertional footprint restoration [54, 56], and more anatomic bone tunnel placements. Few studies have attempted to better delineate the neurosensory anatomy of this region, or the vascularity that could potentially facilitate a more favourable ACL healing response following repetitive strain-induced microtrauma [57]. An improved understanding of these characteristics is important when considering the efficacy of ACL repair rather than reconstruction for some patients [51].

The enthesis is the region in which a tendon, ligament, or joint capsule attaches to bone [58]. Benjamin et al. [58, 59] suggested that entheses are best understood by considering ligament insertions not solely as focal attachment sites, but as parts of an "enthesis organ complex". Ultrasound and MRI imaging suggest that entheses help dissipate bony interface stress concentrations away from the insertion sites [58, 59]. The ACL insertions form a simple enthesis organ with an articular cartilage/fibrocartilage covering, adjacent subchondral bone, and the intervening knee joint cavity. When stress is dissipated away from a bony insertion because of effective enthesis function, pathologic changes may occur at or adjacent to the ACL insertions. Much remains to be learned about the potential for better replicating natural enthesis organ function post-ACL repair, compared to reconstruction.

Native neurovascular cruciate ligament anatomy

The major vascular contributions to the native ACL and PCL occurs at the proximal and distal ends, with minimal central vascularization [60, 61]. Blood supply is primarily provided by middle genicular artery branches which arise from the popliteal artery, penetrate the caudal joint capsule, and pass craniodistally to the fossa intercondylaris, running

cranially between the cruciate ligaments. Cruciate ligament blood supply is primarily of soft tissue origin with negligible osseous contributions. Blood supply is also provided by the medial and lateral genicular arteries, the infrapatellar fat pad, the synovial membranes that ensheath the cruciate ligaments and extensive extra- and intra-ligamentous anastomoses (Fig. 1).

The ACL and PCL insertions are also neurosensory critical areas [11, 13, 62–75] with high concentrations of Pacinian (rapid movement), Ruffinian (stretch), Golgi-like (tension) mechanoreceptors, and free nerve endings (pain) [63, 65, 66, 76]. This complex population of ACL, PCL, CL and meniscal mechanoreceptors provides the central nervous system with information on knee position, movement, and noxious events [11, 70, 77–79]. In addition to transmitting afferent neural signals, nerve branches, primarily from the posterior articular nerve, regulate cruciate ligament vascular dilation [13, 52]. The main articular nerve bundles are located at the stiffer, femoral end of the cruciate ligaments in association with mechanoreceptors that are highly sensitive to subtle movement positioning errors [13, 72, 74, 80, 81]. The middle third of the cruciate ligaments has lower mechanoreceptor density [11, 69, 76, 82]. Other nerves contribute cruciate ligament afferent fibres to a variable extent. Axons radiate toward the centre of the cruciate ligaments from the richly vascular, peripheral synovium [13, 75]. Within the cruciate ligaments, most nerves course along the epi- and endoligamentous blood vessels in the inter-fascicular areolar spaces. As per Hilton's Law [83], nerves that innervate knee region muscles contribute sensory branches to adjacent knee CL tissues [13, 46, 71, 83]. Intramuscular articular nerves occur more frequently in muscles above the knee joint than below it, and are more common in extensor than flexor muscles [76]. These articular nerve dispositions are extremely variable between individuals and no consistent pattern has been identified.

A cruciate ligament-mediated neuromuscular reflex can help protect the knee from injury at motion extremes [10, 13, 69, 70, 74, 84, 85]. Through this reflex, the cruciate ligament sensory system modifies adjacent muscle stiffness to increase dynamic knee stability [10, 11]. This is not conscious perception, but rather it represents a central and peripheral nervous system-mediated reaction to mechanically evoked sensory signals. Even moderate cruciate ligament stretching may induce major neuromuscular joint stiffness and intersegmental lower extremity coordination changes [10, 11]. Neuromuscularly mediated dynamic knee stability reduces CL laxity and increases extrinsic knee joint resistance to de-stabilizing movements. This process becomes impaired with the interruption of afferent impulses from injured CL structures. Loss of joint mechanoreception is part of the degenerative knee OA process [86]. Any combination of repetitive or high-load tibiofemoral joint rolling, rocking, and translational movements may impair cruciate ligament, meniscus and CL tissue function. Localized, primary CL microtrauma may not initially appear to be clinically significant, but with repetitive, progressively larger lesions, or with sudden rupture, biomechanical and neurosensory functions are likely compromised in direct relationship to lesion severity and chronicity [11, 72]. Poorly understood functional significance, path intricacy and network variability has led to ACL reconstruction procedures not routinely attempting to preserve ligament neurosensory function [87].

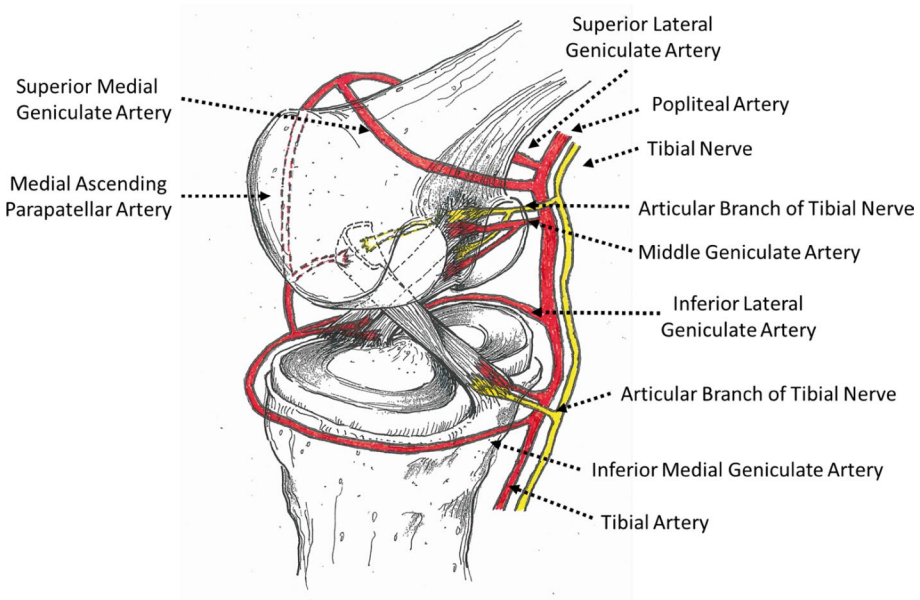

Fig. 1 The knee organ includes intricate vascular anastomoses and cruciate ligament neural branches in addition to its multiple "bundle" or functional "ribbon" morphology

Knee capsuloligamentous stability, mechanoreception, and lesion progression

Variable CL structures neutralize forces resisting knee laxity at different positions [88, 89]. If unrestricted, increased knee flexion is accompanied by increased tibial internal rotation. As the knee flexes, the cruciate ligaments wrap upon each other, and spiral upon themselves. Higher cruciate ligament strain limits the magnitude of tibial internal rotation on the femur. The cruciate ligaments become primary CL restraints to excess movement if there is loss of collateral ligament support. Joint compression and neuromuscular activation greatly assist the joint stability provided by CL tissues. The cruciate ligaments sequentially tighten through full knee flexion–extension in direct relationship to their anatomic locations and orientations within the joint. Different fibres within both cruciate ligaments are stressed with the multi-axial stresses of normal knee function and range of motion. Adjacent intra- and peri-articular tissues act in synchrony as motion constraints in various movement planes (Fig. 2a–c).

Progressive mechanical overload weakens the crimped collagen fibril pattern observed in seemingly healthy cruciate ligaments and further tensile loading causes fascicle disruption. Excessive collagen remodelling predisposes the cruciate ligaments to increased laxity and neurosensory impairment. Joint inflammation and ischemia further contribute to matrix changes and to the neurovascular mechanisms that may be linked to the pathophysiology of cruciate ligament disease [13, 52, 61]. Blood supply to the cruciate ligament core is already marginal and tissue hypoxia associated with micro-injury further weakens the ligament midsubstance decreasing the possibility of any healing bridge formation across the injury site [52, 61]. Because healthy cruciate ligaments are enveloped in a protective synovium layer, they are extra-synovial. Therefore, the collagen tissue that contributes to their biomechanical strength is normally obscured from immunologic surveillance. However, when

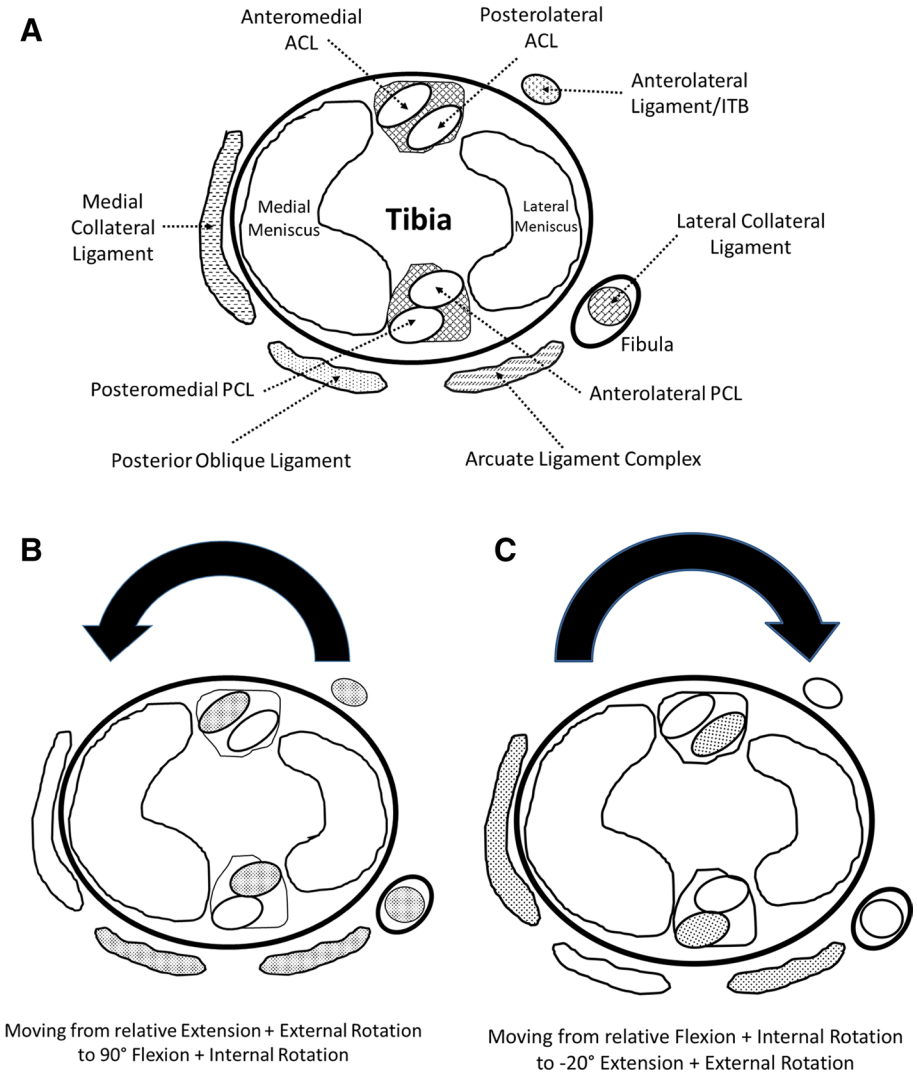

Fig. 2 **a** In conjunction with natural joint arthrology and peripheral capsuloligamentous tissues, the ACL, PCL and menisci form an intricate biomechanical and neurosensory organ with reciprocating cruciate and capsuloligamentous tension that occurs with normal knee motion. **b** *Shaded regions* represent increased tissue tension in the anteromedial ACL bundle, anterolateral ligament, lateral collateral ligament, arcuate ligament complex, posterior oblique ligament, and anterolateral PCL bundle as the knee moves from relative extension-external rotation to 90° flexion-internal rotation. **c** *Shaded regions* represent increased tissue tension in the medial collateral ligament, the posterolateral ACL bundle, the arcuate ligament complex, and the posteromedial PCL bundle as the knee moves from relative flexion-internal rotation to −20° extension-external rotation

this synovial layer is violated as with injury, the exposed collagen may act as a self-antigen, counteracting any tissue healing response. When this occurs, seemingly isolated and uniplanar micro-traumatic cruciate ligament lesions may progress to more multi-planar, multi-directional, macro-traumatic lesions and generalized knee joint impairments or sudden failure. This, in combination with CL injury may impair both biomechanical and neurosensory knee function.

Capsuloligamentous system (somatosensory afference)

The posterior articular nerve transmits signals to the posterior tibial and sciatic nerves before synapsing at the lumbar dorsal root ganglions entering the spinal cord between lumbar vertebral level 4 and sacral vertebral level 3 (Fig. 3) [90, 91]. Axons then ascend the spinal cord within the fasciculus gracilis (dorsal columns) and synapse at the nucleus gracilis in the caudal medulla before traversing across the arcuate fibres and ascending up through the brainstem and synapsing within the somatosensory cortex of the brain.

The ACL: brain linkage

Somatosensory information from the knee is integrated with information from the adjacent lower extremity, other body regions, and exteroreceptors (visual, auditory, vestibular systems) to generate a detailed, multi-modal central or "cortical" representation map [92]. Studies of systemic neurophysiological dysfunction and central nervous system reorganization associated with peripheral joint injury is a growing and rapidly changing research area [86, 93–101]. New discoveries in this area are occurring at a rapid rate, and innovative measurement methodologies are becoming more clinically accessible and relevant.

Capsuloligamentous system and neuromuscular control (efference)

The brain cortex motor region creates a motor plan or program designed to optimize the efferent response directly based on the aggregate afferent information that is received. In addition to motor signals transmitted from the primary motor cortex, the premotor cortex provides modulatory, efferent signal refinement while the supplementary motor area supports postural control, bilateral movement coordination, and movement sequence control [92, 102]. Motor signals are transmitted from the primary motor cortex (pyramidal cells in layer V) descending through the posterior limb of the internal capsule, coursing midline to the medullary pyramids, descending via the cortico-spinal tract, and synapsing with lower motor neurons in the anterior horn of the spinal cord (Fig. 4). Motor signals are then transmitted from lumbar vertebral level 2 to sacral vertebral

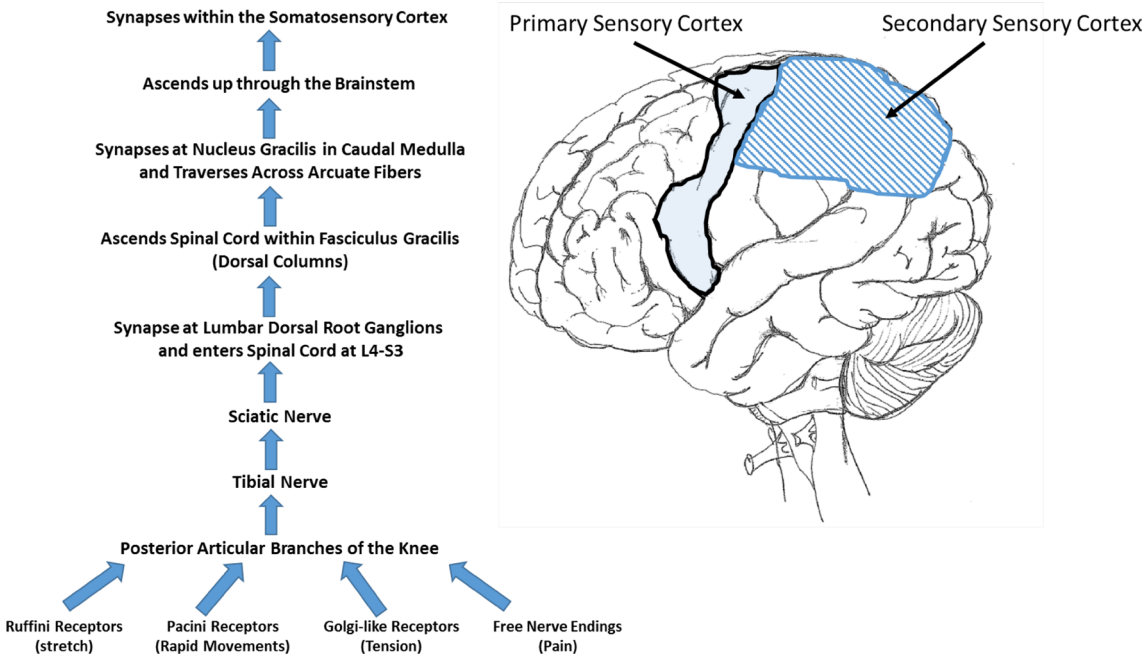

Fig. 3 The neurosensory system transmits afferent information from the knee to the primary and secondary somatosensory cortex located in the posterior parietal region of the brain

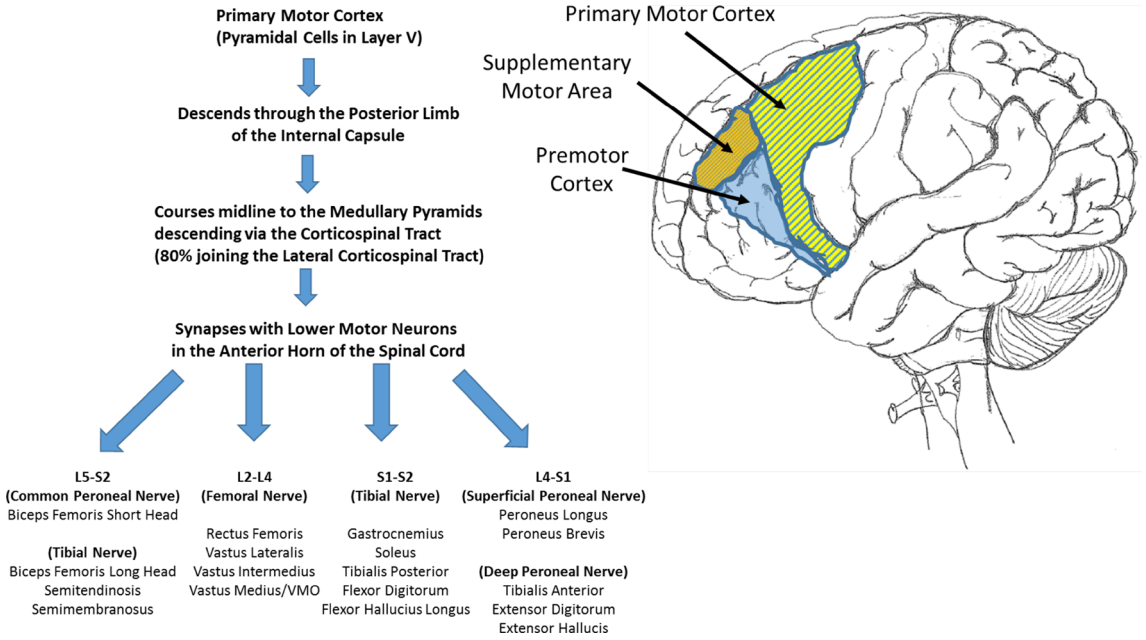

Fig. 4 The neuromotor system transmits efferent information from the primary motor cortex, to the knee region and adjacent lower extremity musculature. The premotor cortex and supplementary motor area provide associated modulatory functions

level 2 to provide motor function to the knee region and adjacent regions beyond the scope of this review.

ACL-brain linkage impairment

With progressive biomechanical and neurosensory impairments, the sensory cortex of the brain receives vastly different afferent transmissions from the knee. In receiving altered afferent contributions, the sensory cortex transmits less accurate three-dimensional knee position and/or movement information to the motor cortex. Because of this, the central representation or "cortical map" of afferent neurosensory signals transmitted to the sensory cortex changes, sharing vastly different afferent transmissions with the motor cortex [38, 103, 104]. With these changes, there may be a greater tendency for the neuromuscular system to evoke maladaptive compensations throughout both the involved and the contralateral lower extremities [39, 95–97, 101, 105, 106]. Absent or significantly altered neurosensory signals from the knee likely propagate a modified motor plan that may bypass or otherwise not focus as strictly on knee region contributions. In the presence of impaired afferent feedback, the modified motor plan likely places greater reliance on afferent information from adjacent, intact neurosensory joints such as the hip and ankle-subtalar joint complex, tending to upregulate more proximal composite lower extremity neuromuscular function through the hip and perhaps also more distally through the ankle/subtalar joints. These motor plan modifications enable continued function; however, they also contribute to the development of compensatory movement patterns [36, 37, 106]. These compensations may become manifest in the modified kinematic, kinetic, and EMG characteristics associated with imbalanced hip–knee–ankle/subtalar joint function. Reduced knee afference, particularly from the injured ACL, produces a concomitant decrease in quadriceps femoris and gastrocnemius fast twitch muscle fibre volume and neuromuscular activation [14, 39, 107–109] in addition to decreased hamstring muscle group activation responsiveness [110]. Associated with this, fast twitch, power generating quadriceps femoris and gastrocnemius muscle fibres atrophy and a functional bias is directed toward greater activation of more postural slow twitch muscle fibres to enable continued performance of less demanding movements in the presence of chronic knee laxity and impaired CL neurosensory acuity [14, 108, 109, 111]. In the absence of optimal quadriceps femoris and gastrocnemius fast twitch muscle fibre function, hip extensor/external rotator neuromuscular activation may be upregulated to increase the direct control of frontal plane hip position and the indirect control of transverse plane knee internal–external rotation through the long axis of the femur, thereby increasing indirect control of sagittal plane knee flexion–extension positioning [39,

112]. Soleus muscle activation may be similarly upregulated to dynamically control long axis tibial rotation through the ankle and subtalar joints.

ACL repair versus reconstruction

The reconstructed ACL no longer transmits neurosensory information to the brain in any way similar to its premorbid state, representing a severely sensory compromised or "dead" zone to the sensory cortex. No matter what graft type, placement, fixation or drilling method, ACL or PCL reconstruction restores biomechanical function much more closely than neurosensory function. Even the fully remodelled ACL or PCL graft never restores native neurosensory tissue characteristics [113]. An accurate analogy might be that the knee surgeon generally performs effective carpentry (restored biomechanical function); however, no electrician (restored neurosensory function) has been hired to complete the job. Because of this difference there is a growing movement to more closely restore the natural ACL or PCL insertional enthesis, and to preserve the proximal and distal mechanoreceptor-rich regions of remaining ACL or PCL remnants and their associated neurosensory properties (particularly on the femoral side) [7, 30, 45, 114, 115]. The primary issue with current ACL reconstruction methods may not be the few millimetres of residual laxity, the couple degrees of impaired proprioception, or perceived function survey point deficits, as much as it may be the lack of central representation or "cortical mapping" that is normally provided by the healthy ACL to the brain sensory cortex [36, 37, 103, 104]. By preserving more natural entheses, native mechanoreceptor dense tissues and existing neurosensory structures (thereby reducing central representation deficits [103, 104]), the repaired ACL has the potential to better match premorbid physiology [116–118]. Post-ACL injury bone mineral density (BMD) decreases throughout the traumatized lower extremity and this decrease is most apparent in the ACL injury region [119, 120]. Studies suggest that BMD improves following ACL reconstruction but never returns to the pre-injury condition [120]. From a BMD, neurosensory and neuromotor perspective, ACL injury creates somewhat permanent effects. Subchondral bone injury is a known precursor to the articular cartilage apoptosis that precedes knee OA.

Biologic ACL repair mediation

Diverse biologic mediator use such as platelet-rich plasma (PRP) [121, 122], and stem cells [123] to enhance ACL healing is increasing despite limited scientific evidence. This trend is occurring in direct association with a growing appreciation for lesion healing potential, preserving both natural ACL mechanoreceptor and enthesis function [51, 116]. Some have recommended ACL repair augmentation with collagen-coated suture, submucosa, or magnesium ring scaffolding [9, 46, 124, 125]. The knowledge base regarding biologically mediated tissue healing enhancement has prompted a surgical management "pendulum swing" away from a solely mechanocentric focus of ACL reconstruction to greater consideration of a biocentric repair approach [126, 127]. Provided it can adequately simulate non-impaired biomechanical function, the more intact neurosensory system of a repaired ACL may enable quicker, more precise neuromuscular activation responses, more robust fast twitch muscle fibre viability, joint position sense and kinesthesia [39, 96, 122].

When scaffolding materials are used, it is important to discern the true balance between the support provided by the healing ACL tissue versus the scaffold material, and whether or not this will change over time. Permanent scaffold material may stress shield the repaired ACL. The end goal for bracing or scaffolding use should be to eventually restore natural ACL biomechanical and neurosensory physiological function. The potential for more natural physiological load transference with surgical repair may eliminate the reliance on large diameter bone tunnels, autograft harvest, and the use of large, permanent fixation devices such as screws and buttons. In combination with mechanoreceptor and enthesis preservation and biologically mediated tissue healing, use of smaller diameter bone channels and fixation devices [125] for ACL repair may become more feasible surgical options.

As knee surgeons develop improved ACL reconstruction or repair methods, they should direct greater attention to restoring the physiological function of all knee tissues. Longitudinal BMD studies that provide evidence of more effective osseous and osteochondral remodelling for a given ACL repair or reconstruction method would suggest superior physiological load transfer through and neurosensory signals from the surgical knee. Rehabilitation strategies should likewise select movement task challenges that blend appropriate biomechanical loads and neurosensory stimulation in a manner that better facilitates tissue healing, remodelling, physiological, and psychobehavioral (increased self-efficacy, decreased kinesiophobia) function at key recovery time periods. This represents a major shift in ACL injury management philosophy and recovery expectations. Much remains to be determined about appropriate patient selection, and long-term outcome efficacy; however, several recent clinical ACL repair studies have shown promising early results [42–44, 128–130].

Motor learning and dynamic knee stability

Preservation of mechanoreceptor dense ACL regions, natural footprints and entheses [58, 59, 131–134], synovial membrane neurovascularity, and the intricate ACL neural network provides the surgeon with many reasons to approach ACL repair or reconstruction from a tissue preservation perspective [135]. The motor learning that occurs as patients perform directional change and sudden acceleration or deceleration movements promotes the development of efficient motor plans that are more adaptable to instantaneous and often chaotic neuromuscular control system and dynamic knee joint stability needs. The motor learning process finetunes motor plan selection and execution with improved adaptability and efficiency. Ideally, the selected primary motor plan decreases intersegmental lower extremity movement variability and knee-specific movement constraint, while also restoring movement task performance variability that better matches premorbid function [112, 136–138].

The brain has a tremendous capacity for positively influencing physical function [18, 92, 139] and much of this capacity is largely untapped by the medical, surgical and rehabilitation communities who provide care to patients following ACL injury, repair, or reconstruction [39, 139]. Fisher et al. [140] used transcranial magnetic stimulation (TMS) motor-evoked potentials to measure brain activation as healthy subjects performed targeted gluteus maximus muscle training exercises. In less than 1 week, improved corticomotor excitability and inhibitory processes were observed, suggesting a strong therapeutic exercise-corticoplasticity influence.

The goal of ACL repair or reconstruction should not solely be to alleviate knee joint instability. Rather, the goal should also be to re-establish the natural biomechanical and neurosensory function that in combination with effective rehabilitation motor learning restores physiological ACL function for neuromuscular control and dynamic knee joint stability purposes. Much remains to be learned about the true impact of ACL neurosensory and biomechanical impairment on brain function. Obtaining a better understanding of BMD changes post-injury, surgery, and rehabilitation, and focused research on sensorimotor cortical integration may provide the most revealing information about the true capacity for ACL repair to more effectively re-establish physiological function. Improving this understanding will help make therapeutic exercise movement task selection more precise, develop more physiologically and psychologically sound evidence-based rehabilitation programs [18, 39], and implement innovative, clinically applicable measurement strategies that better validate the patient's true ability to safely return to intense athletic activities at a high frequency without reduced performance capability.

The path to improved future patient outcomes

Historically, knee surgeons and rehabilitation clinicians have focused primarily on reducing knee laxity and normalizing quadriceps femoris and hamstring muscle group strength post-ACL surgery [98]. Identification of direct ACL load–thigh muscle tone relationships has set the stage for an evolving focus on peripheral and central neural influences on physiological knee function [79, 105, 141–146]. Sensorimotor cruciate ligament attributes are more susceptible to injury than their biomechanical properties [147]. Research has shown that direct electrical stimulation to a healthy ACL activates a hamstring reflex [110, 147–151]. Both in vivo animal [149, 152] and human [153–155] studies have identified likely permanent protective neuromuscular reflex impairments over varying time periods following ACL reconstruction. These deficiencies may be primarily due to cortical sensorimotor impairments rather than the complete absence of ACL-neuromuscular reflexes [47, 149, 153].

The ACL injury research evolution has progressed to directly measuring brain cortex sensorimotor characteristics [156], changes in patient psychobehaviors [18], and changes in intersegmental joint movement coordination variability and knee joint constraint properties [43, 136–138, 157]. Using functional MRI, Shanahan et al. [86] reported that subjects with knee OA had more anterior brain cortical representation loci, had poorer knee task performance, and substituted ankle for knee motor cortex representations more than a healthy control group. Pietrosimone et al. [158] used transcranial magnetic stimulation (TMS) to compare vastus medialis active motor threshold, Hoffman reflex:muscle response ratio (H:M ratio), and voluntary activation differences between patients at 48.1 ± 36 months post-ACL reconstruction (BPTB or hamstring autografts) and a healthy control group. The active motor threshold was higher in the injured than in the uninjured lower extremity of the ACL reconstructed group and it was also higher than the matched lower extremity of the control group. The H:M ratio was bilaterally higher in the ACL reconstructed group compared with the control group. They concluded that higher involved side vastus medialis activation thresholds among ACL reconstructed patients represented post-surgical corticomotor deficits, while higher bilateral H:M ratios represented a strategy to increase reflex excitability. In a similar study, Kuenze et al. [96] identified quadriceps femoris function and cortical excitability measurement asymmetries between patients at 31.5 ± 23.5 months (range = 7–80 months) post-ACL

reconstruction using hamstring or BPTB autografts and a healthy control group. They concluded that measuring these asymmetries post-ACL reconstruction is an essential step to better understanding long-term self-reported function impairments and the increased rate of subsequent knee injury. Ward et al. [159] used TMS to assess corticomotor excitability related to rectus femoris function among subjects at 69.5 ± 42 days post-ACL injury compared to a healthy control group. They found that the cortical silent period (measure of sub-clinical motor system disturbance) was longer at the injured side of the ACL injury group compared to the uninjured side. Baumeister et al. [141] used EEG to compare force sensation and cortical activation between patients at 12 ± 4.7 months post-ACL reconstruction using quadrupled hamstring autografts and healthy control group subjects as they attempted to reproduce 50% of a maximal voluntary quadriceps femoris isometric contraction. The ACL reconstructed group had increased anterior cingulate brain cortical activity and higher frontal Theta power when the surgical side attempted force reproduction, suggesting proprioceptive impairment. In a case–control study, Grooms et al. [95] used brain function MRI during knee flexion–extension to compare a patient post-ACL reconstruction using a BPTB autograft with a healthy, control subject. Measurements were taken after return to sports (10 months post-injury), 26 days prior to sustaining a contralateral ACL injury. The ACL-injured patient had bilaterally increased motor planning, sensory processing, and visual motor control brain cortex area activation compared to the control subject. The authors concluded that altered neurophysiological function may have contributed to the primary knee injury, and that bilateral neuroplasticity post-ACL injury was associated with increased bilateral knee injury risk. Using EMG and TMS methods, Lepley et al. [97] compared the quadriceps femoris cortico-spinal excitability and spinal-reflex excitability of patients before and after ACL reconstruction (BPTB or hamstring autograft) compared to a healthy control group. Patients had decreased bilateral spinal-reflex excitability compared to the control group before surgery and at 2 weeks post-surgery. Patients also had higher active motor thresholds at 6 months post-surgery in both lower extremities. They concluded that rehabilitation should target spinal-reflex excitability early post-ACL reconstruction and cortico-spinal excitability later.

To achieve better outcomes [49, 50], future research needs to improve how to match the individual patient to a specific procedure (conservative care, partial repair, full repair, partial reconstruction, full reconstruction) and rehabilitation progression [34, 135, 160]. Remnant typing [115], mechanoreceptor viability assessments [161], neurosensory recovery potential determination [95, 97] and scaffold support augmentation needs [116–118, 127] will help determine repair viability. In addition to restoring peak lower extremity strength–power [40, 121, 162], and improving thigh and calf girth (fast twitch muscle fibre integrity) [107, 162], verification of more normal sensorimotor brain communication [36, 37, 159] and sensory–visual aspects of motor function and motor learning adaptations [39, 94, 140, 163, 164] during therapeutic exercise performance will become essential elements of outcome assessment. Neurosensory and psychobehavioral aspects of recovery [18, 22, 100, 165] including improved dynamic knee joint constraint and more natural motor control variability [43, 136–138] must be restored. Long-term, longitudinal measurements of these important recovery factors will better elucidate the most effective path to complete functional recovery and validate the true efficacy of ACL injury care.

Conclusion

Surgical restoration of a more physiologically sound knee joint may be essential to solving the osteoarthritis dilemma. Innovative rehabilitative strategies and outcome measurement methodologies using more holistic and clinically relevant measurements that closely link biomechanical and neurosensory characteristics of physiological ACL function with task-specific patient physical function and psychobehavioral factors should better delineate the true efficacy of all ACL surgical and non-surgical interventions.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Funding This study received no funding to complete.

Ethical approval This study did not require ethics approval at its institution.

Informed consent As there was no individual participants in this study informed consent was not required.

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