Neuroscience Principles for ACL Rehabilitation and Reinjury Risk Reduction

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16.1 Anterior Cruciate Ligament Injury

An anterior cruciate ligament (ACL) rupture is a debilitating activity-related knee injury that usually requires surgical reconstruction and extensive rehabilitation to restore knee stability and function [1–3]. The current best evidence suggests that targeting the neuromuscular control system is the key to effective rehabilitation to restore patient function and reduce reinjury risk [4, 5]. The current standard of care for ACL post-surgical rehabilitation is to engage in neuromuscular training, yet a failure rate up to 25% remains following return to activity in young active individuals [6–8]. This high failure rate is further compounded by the majority of individuals not even returning to preinjury levels of activity [9]. This leaves an opportunity to improve current neuromuscular training interventions

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F. R. Noyes, S. Barber-Westin (eds.), *Return to Sport after ACL Reconstruction and Other Knee Operations*, https://doi.org/10.1007/978-3-030-22361-8_16

to ensure return to physical activity levels with optimal outcomes and reduced second injury risk [10–14].

Although evidence supports neuromuscular training for effective injury prevention and rehabilitation, many of these approaches primarily target biomechanical factors such as muscle strength, balance, and plyometric function with less consideration for cognitive or neurological components [4, 5, 15, 16]. While rectifying the biomechanical profile and restoring muscle strength are vital components of the rehabilitation process, there may be potential to further improve function and decrease reinjury risk [17, 18]. Recent reports demonstrate unresolved neuroplastic alterations after injury, reconstruction, and rehabilitation that may be limiting function and the return to sport (RTS) participation [19–21]. These data stem from the foundational concept that the ACL is not only an intra-articular ligament providing mechanical stability to the knee joint, but is also highly innervated with mechanoreceptors that provide afferent signals to the central nervous system (CNS) and injury/reconstruction causes the loss of these mechanoreceptors [22–24]. A simple analogy for ACL reconstruction (ACLR) is that a torn electrical cord can be appropriately put back together, but the cord does not properly conduct electricity in its previous fashion. By targeting cognitive-associated neurological factors during neuromuscular rehabilitation progressions, it may be possible to improve the transfer of sensorimotor adaptations from the clinic to activity, and ultimately improve patient outcomes [25, 26].

16.2 Limitations of the Classic Structural-Mechanical Model

The very nature of the noncontact ACL injury mechanism illustrates the vital role of the CNS to restore function and prevent second ACL injury [27, 28]. The noncontact ACL mechanism is due to a loss of neuromuscular control during activities that can range from simple running to jump-landing and rapid direction changes [29–31]. This noncontact injury scenario demonstrates the need to challenge a broad spectrum of sensorimotor control contributions. The noncontact mechanism has repeatedly been associated with a failure to maintain knee neuromuscular control, while attending to an external focus of attention, involving highly complex dynamic visual stimuli, variable surfaces, movement planning, rapid decision-making, variable player positions and environment interactions, and unanticipated perturbations [32–35].

While many factors, including hormonal [36, 37], gender [38, 39], anatomical [40–43], and even genetic [44–46] influences, have been implicated in injury risk, the primary focus of physical rehabilitation has been dynamic neuromuscular control, since it is modifiable [5, 15, 16, 47–51] and a prospective predictor of primary [52–55] and secondary [7] injury. A great deal of evidence suggests targeting the neuromuscular control system is the key to intervention effectiveness, and the ability to mitigate injury risk may be to optimize the biomechanical-neurological integrated system [4, 5, 48, 56]. However, despite a great deal of biomechanical data to support altered movement strategies that continue to exist despite intervention, orthopedic medicine has only just begun to examine how joint injury influences the nervous system.

Recent research has demonstrated that CNS changes may be more important to sustained optimization of movement strategies than reliance on biomechanical post-test measures alone [21, 57–63]. This suggests that the CNS underlies any modification of injury risk, and to decrease risk, a motor control adaptation is required to adjust the requisite neuromuscular and biomechanically measured change [47, 61, 64–66]. The sustainment of movement strategies to reduce injury risk is highly associated with a neuroplastic motor learning adaptation [67–71]. However, due to limitations of the biomechanical model of musculoskeletal injury assessment, current interventions focus on adaptations made in primarily biomechanical terms that have been shown to revert to pre-intervention levels or not induce improvement at all [10, 12, 66, 72–74].

Current standard of care interventions that target the neuromuscular control system may be missing vital aspects of sensorimotor function because significant deficits in neuromuscular function remain during RTS [4, 5, 75–77]. The best practice neuromuscular control focused programs may be insufficient to fully address reinjury risk or restore patient function [7, 12, 64, 78–80]. It is likely that aspects of sensorimotor function that are affected by the injury are not adequately addressed in therapy, allowing suboptimal neuroplastic compensations to occur [81–83]. Consideration of neurological post-injury adaptations, in addition to restoring mechanical stability, is needed to formulate adjunct therapeutic strategies to improve neuromuscular control.

16.3 Neuromuscular Control

The term neuromuscular control is meant to encompass a spectrum of human function, ranging from the afferent input, the processing of that input, generation of the efferent output, and the overall coordination of the system [84]. Neuromuscular control also has a temporal component in the continuous feedback loops between sensory and motor processing that contribute to the final measurable output [85]. As the muscles contract and bodily segments move, the afferent system is constantly sending new signals to the motor system to update the position, force generation, environmental representation, and other factors relative to the output. This constantly updating system represents the neuromuscular control profile so important to movement control and performing motoric tasks.

To experimentally capture the neuromuscular control system, a largely behaviorist and functionalist methodology has dominated the field with reliance on a postural-structural-biomechanical approach [86]. This prevailing method is concerned primarily with measuring the final output of the system in the form of joint biomechanics without any quantification of the underlying mechanisms that generate those mechanics [9, 87]. This behaviorist or outcome-oriented approach does not account for the extensive neural computations associated with sensory processing along vestibular, visual, and somatosensory pathways which in turn allow for stability and control in the presence of a changing environment [87, 88]. The proprioception, force control, and kinesthetic contributions of the sensory system are vital to the organization of motor output and maintaining neuromuscular control integrity [88]. The ACL is unique compared to most ligamentous structures in that it has robust afferent connections with the spinal cord [89, 90] and cerebrum [24, 91]. This is due to the high volume of mechanoreceptors such as free nerve endings, Ruffini end organs, Pacinian corpuscles, and Golgi receptors in the synovial lining of the ACL that contribute a great deal to afferent function [92–96]. Restoration of these important neurological features has not been well established in the clinical setting, yet may prove to be vitally important to the future function post ACL injury.

The interaction between proprioceptive inputs, such as that from the ACL, and visual input plays a crucial role in providing overall afferent input to the CNS to regulate movement control feedback loops [88, 97–100]. The brain receives somatosensory information in the thalamus and primary somatosensory cortex (via Brodmann’s areas 3-1-2), and then integrates that afferent information caudally in the posterior parietal cortex, areas 5 and 7. This is also where the temporal lobe processed vestibular and visual information integrates with somatosensation before transmitting to the premotor cortex (area 8) and finally to the motor cortex (area 6) to achieve motor drive [85].

Musculoskeletal injuries may alter this flow of somatosensory [19, 81, 101–103], vestibular [104–106], and visual [82, 107, 108] processing in the CNS to sustain motor control. To maintain neuromuscular integrity in the presence of joint injury, the CNS may compensate with altered motor planning [105], regulation of integrated sensory information reaching the motor areas [19, 101], increased reliance on visual feedback or memory [82, 109], and/or alter the cortical-spinal drive [110, 111]. This CNS functional reorganization is most likely due to the mechanoreceptors lost in the damaged tissue contributing to decreased afferent input [92, 93]. This diminished sensory function is present despite years after the injury and normalized strength of the surrounding musculature [81, 83]. This is a likely source of neuroplasticity post musculoskeletal injury; thus, examining methods to address the sensory-visual-motor system along with the neuromuscular system in rehabilitation may improve patient function and decrease recurrent injury risk.

16.4 Neuromechanical Principles of Performance and Injury Risk

Action is the expression of cognitive processes [112], which integrate expectations derived from previous experiences with perceptions of changing conditions in both internal to the body and with respect to the external environment [113]. The term *perception-action coupling* refers to the interdependent nature of neural processes that link sensory inputs to motor outputs [113–116]. The efficiency of perception-action coupling may also be referred to as *neuromechanical coupling*, which has specifically been related to supraspinal modulation in muscle tone to create an optimal state of readiness to respond [117]. Thus, the term *neuromechanical responsiveness* is a designation for the combination of neurocognitive and biomechanical factors that influence the effectiveness of neuromuscular responses to rapidly changing environmental circumstances [118].

A list of common neurocognitive dimensions important to neuromechanical responsiveness can be found in Table 16.1. Vision is the source of sensory input that is primarily relied upon to make decisions about alternative responses to a given external environmental scenario [119], but cognitive processes that interpret visual inputs do not necessarily produce an internal representation that perfectly reproduces every element of the actual scene [120]. Visual-spatial working memory is required to synthesize discrete "snapshot" visual inputs for brain perception of a continuous stream of visual information, with processing informed by memories of past experiences in similar scenarios [121]. Simultaneously, an athlete will process a continuous stream of internal sensory information regarding motor performance, such as balance, proprioception, and force output. The athlete is not only required to attend to these different streams of information simultaneous (i.e., dual-tasking), but typically must be able to process and react as fast as possible in order to maximize their task performance. Because the brain of a given individual provides finite neural resources, rapidly changing circumstances in a highly demanding situation can require selective attention to a limited number of key information processing requirements [119–122]. If cognitive load exceeds neural processing capacity, an athlete may be required to narrow the range of sensory information to which they attend. This may result in "blindness" to unattended visual stimuli or inattention to errors in motor control output [123]. Conversely, when a primary focus of attention does not exhaust processing resources, a larger scope of sensory stimuli may be used to maximize performance [124]. The relative levels of cognitive demand during an athletic task and the cognitive capacity of the athlete may contribute to the overall injury risk of the athlete.

Table 16.1 Dimensions of neurocognitive performance in the sport performance context

Dimension	Working definition
Visual attention	The ability to concentrate on visual input to the exclusion of other less essential stimuli
Self-monitoring	The ability to focus on proprioceptive kinesthetic feedback
Agility fine motor skill	The ability to make minor adjustments in motor activity
Processing speed/reaction time	The ability to engage in stimuli-response behavior within an intended time frame
Dual tasking	The ability to engage in two activities at the same time to maximize goal attainment

A practical example of this dynamic may be seen in the case of a running back in American football who is attempting to advance the ball downfield. The running back must use visual and spatial cognitive resources to attend to an evolving field of play, such as the location of his blocking linemen, the angles of pursuit of opposing linebackers, and his own position relative to the boundaries of play or first down marker. This information is continually compared to prior memory formed by practice of the play or prior game experience. At the same time, he is processing this external information, the running back is processing internal feedback of his own motor performance and interaction with the environment, such as a wet playing field, and then responding as needed to make alterations to his motor control. The player also needs to be able to process and react to these streams of information as fast as possible in order to maximize the yardage gained on the play. If there is a significant mismatch between his capacity for cognitive processing and the cognitive load imposed during task performance, the running back may be at increased risk for injury. This may manifest by a contact injury mechanism, whereby the running back is unable to adequately prepare to receive a hit in a safe manner from a player in his peripheral vision to whom he was unable to devote attentional resources. Similarly, this increased risk of injury could result from a noncontact mechanism, possibly due to a lack of attention to or errors in processing of internal feedback of motor control while prioritizing the processing of external sensory information.

This concept of neuromechanical responsiveness has been demonstrated in prior studies. Normal individuals ranging from military recruits to high-level collegiate football players who perform in the lower range of neurocognitive reaction time have been demonstrated to be at increased risk for musculoskeletal injuries [125, 126]. This effect has also been demonstrated with respect to ACL injury risk specifically, with one study finding that ACL-injured collegiate athletes demonstrated lower levels of preinjury performance across a range of neurocognitive domains, including visual and verbal memory, visual motor speed, and reaction time [127]. Similarly, biomechanical performance of athletic tasks associated with ACL injury risk has been shown to degrade with cognitive loading [128, 129], while athletes with poor memory, reaction time, and visual processing scores demonstrate worse biomechanical performance on biomechanical measures associated with an increased risk of ACL injury compared to athletes with good neurocognitive scores [130]. This relationship can be complicated by fatigue, which is a well-known risk factor for injury and has been shown to interact with cognitive demands to adversely affect the lower extremity biomechanics of female athletes during single-leg jump landing [114, 131]. Fatigue may exacerbate the adverse effects of other conditions or injuries on neural processing capacity, thereby increasing susceptibility to lapses in attention, distractibility, and inattentional blindness to environmental stimuli in the peripheral visual fields.

The dynamics of the relationship between cognition and biomechanics are further strained after ACL injury. Rupture of the ACL eliminates an important source of mechanoreceptor input to the CNS [24, 132, 133], and may have profound implications for maintenance of dynamic knee stability [117]. First, increased activation of brain areas that focus attention and process sensory information suggests that a greater volume of neural resources are required to control knee displacements [101]. Second, brain reweighting of sensory inputs increases reliance on vision for motor programming [107, 134], which has also been demonstrated in other ligamentous injuries such as chronic ankle instability [135]. These increased demands on neural resources may impose critical limitations on the ability to perform simultaneous visual, cognitive, and motor processes, thereby compromising neuromechanical responsiveness. Susceptibility to a poor functional outcome from an ACL injury or to a second ACL injury may be increased by low preinjury neurocognitive performance, the subsequent neural maladaptation from the injury, or a combination of the two [136, 137].

While brain activation patterns can exhibit dramatic changes following injury, activation patterns can similarly respond to training and open a new pathway for rehabilitation subsequent to ACL injury [138–142]. Training approaches may be used to enhance cognitive processing and diminish neural maladaptation from the injury. Due to the value of visual information during athletic tasks for performance purposes and the increased reliance on visual information in the absence of proprioceptive information from the

ACL, visual-cognitive training during rehabilitation may be important for the attainment of desirable neuroplastic adaptions. Choice responses to visual stimuli that involve whole-body movements may be advantageous for strengthening of functional connectivity that integrates neural networks for visual-cognitive and motor tasks [138–148]. Such functional network integration may explain enhanced automaticity of multitask responses that coincide with reduced neural activation of circuits linking the primary visual cortex, primary motor cortex, and cerebellum [139, 149, 150]. Thus, assessment and training activities should combine focused attention, visual stimulus discrimination for rapid decision making, and execution of compound motor skills [116, 150–152]. A number of computerized systems are now available to clinically assess and train the multiple interrelated aspects of neuromechanical responsiveness, including the capability for motion tracking of whole-body reactive responses to visual targets appearing within a virtual reality environment [58, 116, 152].

16.5 ACL Specific Neurological Adaptations

The overarching theory underpinning neuroplasticity from ACL injury is that the CNS afferent input is disrupted due to the lost somatosensory signals from the ruptured ligament and increased nociceptor activity associated with pain, swelling, and inflammation. The disrupted sensory input and injury-associated joint instability, muscle atrophy, and movement compensations combine to induce motor control adaptations. The reconstruction process leads to further deafferentation of the joint, causing continued neuroplastic modifications that result in maladapted efferent neuromuscular output [136].

In animal models, the ACL mechanoreceptor and afferent connections can be traced within the nervous system to the spinal cord, brain stem, and cerebral regions that contribute to proprioceptive, nociceptive, and reflex function [89, 91]. The initial sensorimotor neuroplasticity after ACL injury is likely caused by the abrupt loss of this connection that once provided the nervous system with continuous feedback [92–96, 153]. In human studies, the afferent loss is demonstrated by altered or absent somatosensory-evoked potentials with stimulation of the common peroneal nerve [24, 102, 103, 133] or, in surgery, of the ACL directly [154]. The loss of primary afferent information, combined with the pain and inflammatory responses, contributes to fundamentally alter the somatosensory feedback [107, 155–157]. The disrupted input, combined with mechanical changes and compensations [158, 159] (contralateral loading [80, 160], hip or ankle strategies [17, 161]), facilitates the adaptations for motor control [134, 162, 163]. On a foundational level, the altered motor output is displayed by disrupted gamma motor neuron function [163–165] and perturbation reflexes [162, 166] that play a key role in the ability to maintain neuromuscular integrity in a changing environment, requiring rapid and precise muscle stiffness or activation strategies [167–169]. The lost ability to rely on reflex and gamma motor neuron drive to prepare alpha motor neuron function requires the CNS to engage in supplementary mechanisms such as increased utilization of visual feedback to maintain the required sensory input for motor control [136, 170, 171]. As such, neuromuscular control after ACL injury may require enhanced visual feedback or memory reliance, depriving the CNS of resources once used for managing environmental interaction to maintain knee joint stability.

These deficits in neural function are not rectified with ACLR, as they may in fact become even more pronounced and/or present bilaterally [24, 110, 111, 165, 172–174]. The bilateral motor control, reflex, and proprioceptive changes are theorized to be due to both spinal [89, 91] and supraspinal [103, 175] mechanisms [176]. This ongoing neuroplasticity and altered mechanical and biological function of the joint combines to reduce proprioception acuity as measured by joint position sense [177, 178], movement detection [179, 180], and force sense [181]. To investigate the neurological adaptions of functional sensory loss, Baumeister et al. used electroencephalography (EEG), during force and joint sense tasks, and found that those with ACLR had greater brain activation in attentional and sensory areas [19, 101]. The increased activation may be attributed to less neural efficiency, or increased neural load to complete the same task; interestingly, despite increased cortical activation, proprioceptive performance was still worse in those with ACLR as compared to controls [19, 101]. These results indicate the loss of the native ACL not only constitutes a mechanical instability but a degree of nervous system deafferentation that is not rectified with reconstructive surgery and rehabilitation [153]. This partial deafferentation is further illustrated by investigations utilizing transcranial magnetic stimulation (TMS) to assess the CNS efferent pathway between the quadriceps and the brain [175, 177, 182, 183]. Heroux and Tremblay reported enhanced resting corticomotor excitability in those with ACL injury [182]. A potential mechanism for increased resting motor cortex excitability may be the altered sensory feedback, as the brain attempts to maintain motor output with attenuated sensory input. This increase in excitability may increase potential feed-forward mechanisms by decreasing the threshold for connections with motor planning areas, or allowing for increased input from other sensory sources (vision, vestibular) [184–187].

A neuroimaging investigation by Kapreli et al. [107] provided initial evidence of the neuroplastic effects of ACL injury. They performed functional magnetic resonance imaging (fMRI) of the brain during knee extension-flexion and found those with an ACL injury had increased activation of the pre-supplementary motor area, posterior secondary somatosensory area, and the posterior inferior temporal gyrus (pITG), compared to matched controls [107]. The pre-supplementary motor area is highly involved in complex motor planning [188, 189], and despite the relative simplicity of the movement task (single joint movement of 40° of knee extension-flexion while laying supine), those with an ACL injury needed to engage higher level motor control areas to a greater degree to execute the movement. This increased activation possibly indicates that on a neural-control level, simple movements are more taxing to those with a previous ACL injury [190]. The increase in posterior secondary somatosensory area provides further evidence of sensory-based neuroplasticity after injury, as this area is involved in regulating painful stimuli, but highly interconnected with the anterior secondary somatosensory area that integrates somatosensory inputs [169, 191, 192]. Interestingly, the participants in the study did not report pain during the movement, conceivably indicating a sensory processing adaptation from the initial increase in nociceptive input from the traumatic nature of the injury and not an acute effect. Alternatively, the prolonged nature of the rehabilitation, chronic pain, or joint instability may continue to disrupt typical somatosensory system afferent integration. The pITG plays a role in many cerebral functions [193, 194] but may primarily be involved with visual processing of movement [169]. As such, an increase in pITG activation during movement may indicate that in response to ACL injury there is an increased utilization of visual processing and motor-planning resources for movement concurrent with depression of somatosensory function [24, 82, 102, 103, 107, 133]. The findings of Kaperli et al. were also confirmed in ACLR patients with similar altered visual-motor and sensory-motor brain activation, potentially indicating shifts in cortical-subcortical processing and sensory reweighting [137, 171].

16.6 Neuroplasticity in Sport Rehabilitation

The transition from rehabilitation to sport activity is challenged by complex environmental interactions that place high demand on cognitive and sensorimotor processes and, in turn, increase ACL reinjury risk [32–35]. In a constantly changing environment, the primary afferent pathways (vestibular, visual, and somatosensory) interact to integrate and contextualize the feedback necessary for the efferent neuromuscular control system to maintain adequate stability and control [87, 88]. One area of sensorimotor function that may uniquely be affected by ACL injury is motor control requiring visual feedback [87]. The visual system provides a fundamental mechanism for coordination, regulation, and control of movement while managing environmental interactions (external focus) [109, 195, 196]. The need for visual feedback is especially true in executing movement sequences [189, 197] and with increases in task complexity and variability [196, 198–200]. The interplay between vision and somatosensation is particularly vital to provide sufficient afferent input to the CNS to regulate motor control and maintain neuromuscular integrity during action and environmental interaction [88, 97–100]. In this sensory-to-motor feedback loop, changes to visual or sensory feedback lead to subsequent alterations in neuromuscular control during movement (closed-loop processing) [23, 87, 88, 97, 99, 196].

Rehabilitative exercises are typically completed with an internal focus of control, meaning full attention is being directed to the internal aspects of the movement only (e.g., avoidance of excessive knee valgus or increasing knee flexion) [5, 22, 201]. Such an internal focus can offer positive benefits early in rehabilitation, when the need to develop or restore a motor pattern or muscle contraction ability is vital. However, function in the athletic environment, or even activities of daily living, requires constant interactions with the dynamic and constantly changing visual environment. Sport and activities of daily living, therefore, require an external focus of control, where attention is directed to the environment and the body relies on automatic motor control to maintain joint-to-joint integrity [200, 202, 203].

The need to challenge a broad spectrum of sensorimotor control is demonstrated by the noncontact ACL injury scenario itself: a failure to maintain knee neuromuscular control, while attending to an external focus of attention, involves highly complex dynamic visual stimuli, variable surfaces, movement planning, rapid decision-making, variable player positions and environment interactions, and unanticipated perturbations [32–35]. The need to bridge the intense neurocognitive and motor control demands of sport during rehabilitation may, therefore, benefit from specific interventions that target these neurological factors in addition to the biomechanical techniques that are already widely addressed.

Trauma to the ACL has been shown to modify how the nervous system processes the integration between vision and somatosensation [81, 82, 107, 108, 204]. By targeting injury-induced sensory-motor plasticity, a unique opportunity exists to improve the translation of neuromuscular system enhancements from the rehabilitation environment to the return to sport environment [58, 114, 131, 205]. The combined afferent neuroplasticity due to the lost mechanoreceptors of the ACL [94–96] and efferent neuroplasticity due to arthrogenic muscle inhibition [206] and disrupted gamma-motor neuron feedback loops [173] may induce specific central nervous system compensations. We have found that the CNS will increase reliance on visual feedback to program motion [136, 137, 171, 207–209]. Despite the injury, the nervous system continues to sustain motor output in the presence of depressed proprioceptive input [81, 82, 210] which may force increased use of visual-related feedback (memory or directly) by the motor cortex. This may also be partially induced, during rehabilitation, as therapy is strongly targeted at increased quadriceps activation immediately after surgery with a constant focus of attention on the knee joint; thus, the nervous system may create this visual-motor link during recovery.

Courtney et al. [102, 103, 162] in a series of works demonstrated that ACL-deficient individuals that went on to become copers (positive outcome without surgery) and adapted their movement strategy with increased hamstring activation to compensate for the instability had absent somatosensory-evoked potentials in the brain from the ACL. This was in opposition to noncopers or those that needed surgery or had a poor outcome having intact somatosensory-evoked potentials and no adaptation in motor control strategy. This work indicates that, if the brain does not receive the disrupted or absent afferent signal from a damaged ACL, no motor adaptation will occur. Any peripheral or spinal adaptations that mitigate the loss of the somatosensory-evoked potential at the brain actually resulted in a poorer outcome [211, 212]. This is further supported by recent work of Pietrosimone and colleagues who demonstrated that, after ACLR, those that have the lowest quadriceps activation failure, highest strength, and best reported outcomes have the greatest increase in cortical excitability [175, 178, 211, 212]. This may indicate that unique cortical mechanisms underpin recovery from injury and increased top-down and feedforward mechanisms can compensate to a degree the resulting instability and depressed afferent feedback form the injury.

16.7 ACL Injury Induced Sensory-Visual-Motor Processing Compensations

Neuroplastic observations following ACL injury are supported by biomechanical evidence, suggesting that with increased task complexity, neuromuscular control is deteriorated in individuals with an ACL injury or reconstruction to a greater extent than controls, possibly due to overload of motor planning resources [213, 214]. The specific neuroplastic visual-motor control adaptation is observed during static balance as those with ACL injury have significantly diminished postural control when vision is obstructed (blindfold or eyes closed) [108, 215], but limited to no degradation in postural control with eyes open, as they are able to use vision to compensate and maintain balance [216, 217]. A more pronounced effect on neuromuscular control is observed when disrupting visual-motor processing during complex landing and cutting maneuvers that play an even greater role in injury risk [218–220]. The simple addition of a target, during a jump-landing task, increased injury risk mechanics [221]and altered muscle activation, decreasing postural stability [222]. The effects of forcing visual focus on the environment during more complex cutting or direction change tasks further degrades neuromuscular control capability in healthy athletes with the addition of a defender [219], a virtual soccer interface [223], or a level of unanticipated decision making during the task (selecting direction) [224, 225]. The effect of occupying the visual system with environmental cues during landing or change of direction has an even greater effect on those with ACL injury history [28, 213]. Furthermore, adding an anticipatory component that integrates visual processing and reaction time further demonstrates a reduction in knee neuromuscular control [226]. The inclusion of short-term memory and online decision-making also demonstrates specific adaptations in the maintenance of joint-to-joint neuromuscular integrity during complex athletic maneuvers such as cutting or sidestepping [114, 225, 227–230]. Recently, examination of injury risk, comparing ball-handling or offensive action (considered anticipatory and feedforward in nature) vs. defending (considered unanticipatory and responsive in nature), demonstrated a higher risk with defensive action [231]. This large-scale epidemiological data further support the possible increased injury risk movement strategies when unanticipated, rapid decision-making and/or visual-motor feedback is altered during the laboratory biomechanical studies.

These findings, taken together, suggest that ACL injury may lead to a cascade of neuroplastic and neuromuscular alterations that increase reliance on visual feedback and cortical motor planning for the control of knee movement. The post-injury disrupted sensory feedback, combined with the observed motor compensations, contributes to fundamentally alter the CNS mechanisms for motor control [19, 24, 92, 94, 96, 101, 111, 133]. In attempting to regulate neuromuscular control in the presence of decreased somatosensory input, the nervous system supplements with increased motor planning, conscious cortical involvement, and greater reliance on visual feedback. This ACL injury induced neuroplasticity can have consequences for function and further injury risk as the visual feedback and motor planning neural mechanisms become overloaded in the athletic environment. Specific additions to current neuromuscular interventions, targeting these neuroplastic imbalances, may play a significant role to induce sensory-motor adaptations to decrease dependence on visual feedback when transitioning to more demanding activities [232, 233].

The application of neuroplastic constructs during neuromuscular rehabilitation to optimize musculoskeletal therapy interventions is a new frontier for orthopedic care. The opportunity to supplement traditional interventions by further targeting neuroplastic, cognitive, and visual-motor capabilities is an exciting time for research and clinical practice. These new approaches allow clinicians to approximate the neurocognitive demands of higher intensity athletic activity in a safe, controlled, and most importantly feedback rich environment before reintegration into sport. Recognition of the visual-motor implications in neuromuscular control, injury recovery, and prevention, combined with new technologies, may help to mitigate post-injury movement dysfunction and decrease injury risk when returning to activity.

The training, and even restoration, of primarily biomechanical factors relative to ACL injury risk [52, 234] may not be addressing all the physiologic consequences of the injury, as even years post injury, patient-reported dysfunction and poor movement control persist [79, 80, 83, 159, 235, 236]. The impaired physical performance and patient-reported dysfunction might in part have a neurological origin [107, 173, 175]. The capacity for neuroplasticity, after injury and during therapy, presents an avenue to close a gap between rehabilitation and activity by targeting a broader spectrum of sensorimotor function during neuromuscular training [12, 16, 64, 79]. Alternative approaches and adjunct therapies may help to address the neurological system functions associated with the faulty movement patterns underlying ACL reinjury risk [7, 101, 111, 155].

A possibly overlooked factor in ACL injury prevention and rehabilitation design is visual-motor control associated with maintaining neuromuscular joint-to-joint integrity while engaging in the complex athletic environment [35, 237]. As physical activity and athletic participation require high demand on the visual-motor system to maintain environmental interaction as well as neuromuscular integrity, visual disruption in rehabilitation may be a promising tool to more closely mimic sport demands. The ability to sustain motor control in the variable sport environment demands a complex CNS integration of a constantly changing profile of sensory inputs including visual feedback, proprioception, and vestibular equilibrium to maintain neuromuscular control [87, 88].

The increased visual-motor activation in those with ACL injury suggests an adapted motor control strategy that may not be rectified with current rehabilitation methods. Advancing the neuromuscular control challenge during rehabilitation and prevention strategies can facilitate neuroplasticity not only for the motor regions, but also improve sensory integration and, thereby, address the visual processing bias. The key to this training is to consider the focus of attention, task complexity, visual input, and cognitive load during rehabilitation [114, 225]. Many mechanisms are available, including incorporating reaction time components [225], ball tracking, engaging other players [217], adding decision making [114] or anticipatory aspects [225] and having the patient dual task [214] by engaging the upper extremity while doing lower extremity exercises, or simply occupying the mind with memory or related tasks, can all increase the neural demand of our neuromuscular training strategies. Additionally, as eyes closed or blindfolded conditions have a greater effect on balance and movement performance in those with ACL injury, incorporating them during rehabilitation may address the visual-motor neuroplasticity [82, 108]. New technologies such as stroboscopic glasses provide a means to directly perturbate the visual-motor system under a variety of novel conditions that may help the transition back to the athletic environment, where visual attention is constantly distracted [238, 239]. Previous research using vision obstruction (blindfold) demonstrates alterations in landing neuromuscular control that may increase injury risk [240, 241]. Due to the method of limiting vision, these investigations lacked generalizability and sport specificity as the tasks were simple single movements without environmental interaction. The development of stroboscopic glasses that disrupt vision, without completely removing it, now allows visual-motor assessment during dynamic movements and target acquisition tasks. Stroboscopic glasses technology allows the patient to engage in neuromuscular training under depressed visual feedback and increased cognitive load in a safe clinical environment. This ability to train under a visually disrupted or knockdown stress may provide a means to target unique neuroplastic factors in rehabilitation [242, 243]. The consideration of visual-motor approaches during injury prevention and rehabilitation programs may provide a means to further improve intervention effectiveness. These approaches can be paired with foundational neuromuscular techniques for optimizing strength, multiplanar knee and trunk control, and movement asymmetries [244]. The use of a direct visual disruption technology such as stroboscopic glasses provides an opportunity to supplement traditional interventions [214, 242]. The clinician can add another training area that may decrease injury risk by targeting visual-motor processing along with the traditional neuromuscular, strength, and movement dysfunctions [170, 245]. The cognitive approximation of the demands involved in higher intensity athletic activity under the supervision of a well-trained clinician may further decrease musculoskeletal injury risk. Recognition of the visual-motor implications for maintaining neuromuscular control and injury avoidance may help to mitigate injury risk.

While the suggestions above provide a direct method to challenge the visual-motor system during high level dynamic movements, training the visual processing system in isolation may also have a beneficial effect on neuromuscular control. Swanik et al. provided prospective evidence for decreased visual processing speed as a risk factor for primary ACL injury [127]. Swanik et al. [127] prospectively reported that decreased aspects of neurocognitive function increased the risk of experiencing a noncontact ACL injury. Specifically, reaction time, visual processing, and memory, measured via a computerized concussion baseline assessment (IMPACT), were significantly lower than matched controls [127]. The role of visual-motor function and reaction time to facilitate preparation of the neuromuscular system in anticipation of high-risk situations, maneuvers, or incoming players, provides the theorized mechanism for neurocognition to influence musculoskeletal injury risk [246, 247]. Faster reaction time or processing speed may increase the potential to prepare for incoming perturbations or cognitively manage the complex athletic environment, while maintaining neuromuscular control. Visual training has been shown to improve reaction time and visual processing ability related to sport performance and may be worth considering as an aspect of neuromuscular reeducation [238].

If visual-motor processing ability is suboptimal, this may decrease the ability to compensate for external stimuli and/or attenuate the rapid and sometimes unanticipated maneuvers that depend on quick visual-motor interaction [222, 226, 248]. Visual-motor processing is imperative to successful sport function, whereby complex sensory and visual feedback must be handled with minimal preparation time [35, 246]. Visual memory ability may also assist in motor planning during activity as the constantly changing environment (player or ball positions) must be kept in short-term visual memory when planning movement sequences [243]. While limited connections exist relating biomechanical, visual-motor function, and changes induced by ACL injury, previous reports indicate altered neuromuscular control during visual-motor environmental interaction that may influence injury risk mechanics in healthy active participants [114, 219, 221, 226, 227].

16.8 Use of Neuromechanical Principles in Clinical Settings

Traditionally, ACL rehabilitation has focused on remediation of peripheral biomechanical impairments such as ligament laxity, restricted joint motion, and muscle weakness through techniques involving strength, flexibility, balance, and plyometric training in order to return athletes to competition after injury and reduce risk of ACL reinjury [249]. Utilization of neurocognitive training techniques is less common and presents unique challenges to the clinician and/or coach. Not only do athletes present with high variability in physical ability, especially in youth sports, but neurocognitive ability may vary even among athletes with similar physical attributes. In addition, many of the published studies to date using the computerized systems noted previously are potentially cost prohibitive and may be unavailable to most athletes with ACL injuries. Even if such resources are available, the volume of practice likely required to develop neurocognitive skills may compete with already busy training schedules. Finally, tailoring training programs to the unique abilities of the individual athlete as opposed to mass application of neuromuscular programs may hinder large-scale implementation of such strategies. Nonetheless, the massing body of evidence linking neurocognitive function to injury rink cannot be ignored and clinicians must consider all variables when developing programs intended to reduce risk of ACL injury or reinjury.

When implementing neurocognitive training alongside traditional training techniques, care must be taken to monitor task complexity as to not compromise performance. It is well documented that as cognitive demands increase physical performance will decrease [250, 251]. Prior to placing challenging neurocognitive demands on an athlete, a baseline musculoskeletal profile must be established, taking into consideration the athlete's age, skill level, sport, and position. A youth athlete without a basic understanding of body mechanics and movement strategies cannot be expected to maintain the desired knee position while undergoing a high degree of cognitive load. It is therefore advisable that adequate neuromuscular control be achieved prior to progressing cognitive demands. In addition, inexperienced athletes may also perform more poorly in neurocognitive tasks [252] and may have varying ability to process neurocognitive demands, especially if out of context with their sport.

As athletes develop motor skill and move from the cognitive to associative and autonomous stages of motor learning, the training environment should transition from achieving desired performance to facilitating long-term motor learning. As such, the amount and type of feedback should be systematically reduced while simultaneously increasing the complexity of the task environment. One such strategy involves adding cognitive challenges to be performed in conjunction with the physical task (Table 16.2). Often used cognitive tasks include serial sevens, serial threes, spelling words backwards, controlled word association (COWA), and the Stroop task. While these tasks are not specific to sports, they are commonly used to assess an individual's concentration and memory and serve to simulate the volume of information that must be processed during athletic competition.

In addition to cognitive load, an athlete's ability to respond to stimuli may be influenced by their ability to visualize their environment and detect moving targets. In the context of ACL injury, the athlete's ability to react to varying visual or auditory stimuli and then execute the desired motor pattern at high speeds is vitally important. In a training or rehabilitation setting, simple oculomotor exercises may be implemented to ensure

Table 16.2 Cognitive tasks

Serial 3's/7's	Participant asked to perform mental arithmetic, counting backwards from a predetermined number by increments of 3 or 7	Working memory/ attention and mental concentration
Phonemic and semantic word generation (i.e., Controlled Oral Word Association Test/COWAT)	Participant asked to spontaneously produce words belonging to the same category or beginning with the same letter	Executive function (initiation, strategy use, set maintenance, flexibility)
Stroop color and word task	Participant visually presented with a series of words naming different colors, each word is printed in either the color represented or a different color ink (e.g., the word "red" but in blue ink). The participant is asked to name the color of the ink, ignoring the meaning of the word	Selective attention/ inhibition
Digits backwards	Participants are orally provided a string of random numbers which they are asked to repeat in reverse order. The string becomes increasingly longer, provided correct responses given. Working memory/ attention	Working memory/ attention

precise visual skills. The most common trained movements are pursuits, saccades, and convergence. In a subset of individuals, oculomotor impairments have been linked to deficits in neurocognitive scores [253]. Oculomotor training progressions may include self-paced saccades, Hart Charts, pencil push-ups, and Brock strings (Table 16.3). In addition to oculomotor tasks, one cannot neglect the degree of head movement that occurs in sport, as such vestibular training may be of added benefit. Head velocities of up to 6000 deg/s have been detected in running, with an error as small as one degree resulting in visual distortion thus impairing an athlete's ability to detect stimuli [254]. Vestibular training techniques include balance training and adaption exercises, termed vestibular ocular reflex (VOR) exercises. The effectiveness of such exercises has been well documented in individuals with inner ear pathology [255]; however, the effect on athletic performance has not yet been established. Both oculomotor and vestibular exercises may be progressed by manipulating the environment from simple to busy and transitioning targets from predictable/stationary to unpredictable/moving. Coaches and clinicians may use simple hand gestures, cue cards, computer programs, or actual sports equipment/balls as visual targets. As athletes master each task, additional physical demands should be placed on the athlete to simulate the demands of their sport.

Table 16.3 Vision exercises

Saccades	Self-paced saccades	Participant looks back and forth between two targets as quickly as possible
	Hart chart	Participant reads a series of numbers, letters, or symptoms presented in columns. May be read horizontally or vertically in a variety of different patterns
Convergence	Pencil pushups	Participant holds a target (i.e., pencil) in front of your face at a comfortable distance, then moves the target towards their nose focusing on the target with both eyes until they can no longer maintain single binocular vision. The target is then slowly moved away from the participant and the movement is repeated
	Brock strings	Multiple beads are placed on a string. One end of the string is held at the participants nose, the other is fixed some distance away (distance may vary 1–3 m). Participate is asked to focus on the first bead, then the second, and so on until they reach the last bead, at which point the process is repeated in reverse order
Pursuits	Smooth pursuits	May involve tracking any moving object at speeds slow enough as to not elicit saccades

One criticism of sports vision training is a potential lack of transfer to performance on the field. It is therefore essential, in current context, that visual and cognitive training be made to replicate the unique demands of the sport and position. For example, a soccer goalie will require a high degree of hand-eye coordination, but may not need the ball-handling skills of a mid-fielder. In contrast, all positions in basketball require some degree of hand-eye coordination in addition to lower body quickness and agility. It would not be expected for the soccer midfielder to perform at the same level as the goalie in an object detection and interception task, but the midfielder may exhibit a higher degree of lower extremity control in the presence of cognitive loads.

Table 16.4 represents a sample progression of basic movements often used in athletic training routines. The base movement is first made more difficult by the addition of a single visual or cognitive task, and then by the combination of visual and cognitive tasks (Fig. 16.1). If the athlete can accomplish the movement within the desired parameters, the movement may be progressed; in our example, a squat is progressed to depth jump and the sequence is repeated. The exercise continues progressing towards more sports-specific movements to include directional jumping, responding to a variety of cues. Ideally, these movements are progressed to on-field practice with actual opponents as visual cues.

Table 16.4 Example exercise progression (simple → complex)

Squat	Squat + ball catch **OR** serial 3's	Squat + ball catch AND serial 3's	Depth jump	Depth Jump + serial 3's	Depth jump + Simple RT (jump right or left after landing)	Depth jump + Choice RT (jump right if red card, left if black card)
Agility	Lateral shuffle + Ball catch **or** COWAT	Lateral shuffle + Ball catch **and** COWAT	Multi-directional agility (i.e., 4 cone/square drill[a] with predetermined directions	Square drill[a] + COWAT	Square drill[a] + Simple RT (coach points to cone)	Square drill[a] + Choice RT (jump right if red card, left if black card)

Serial 3's, see Table 16.2
COWAT controlled oral word association test, *RT* reaction time
[a] Square drill: see Fig. 16.1

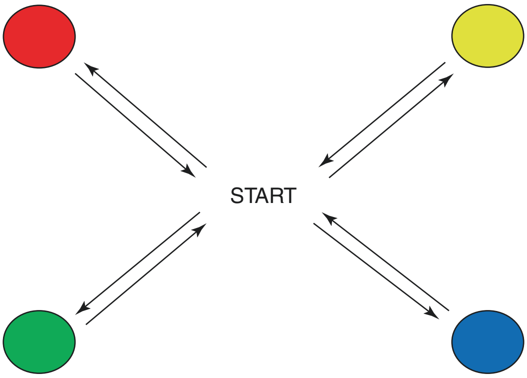

Fig. 16.1 Square drill. Colored flash cards may be used to indicate the target to the patient. A monitor may also be used to display colors via a program such as Microsoft Powerpoint at regular intervals, with the interval increased or decreased depending on the patient's abilities

16.9 Case Examples

16.9.1 Case 1

A 22-year-old female presented status-post ACL repair from an injury occurring during intramural soccer, and with a history of contralateral ACL repair 4 years previously. The patient reported that her rehabilitation and RTS progression after her first surgery only included predictable motor demands and that she never fully regained confidence in her ability to protect herself from future injury, even during simple running tasks. Despite this, she returned to soccer, only to tear her contralateral ACL. For her current injury, the patient progressed as expected through initial phases of the rehabilitation protocol. The addition of cognitive tasks was used to further challenge automaticity of the skills being developed. After exhibiting sufficient strength and balance, agility drills were implemented with progression to unanticipated direction changes utilizing a flanker and Stroop task to challenge concentration. After completing rehabilitation for her second ACL reconstruction, the patient stated her confidence was significantly higher and she planned to continue to include the cognitive demands in her training routine.

16.9.2 Case 2

A 12-year-old female was referred to physical therapy for patellofemoral pain syndrome, with worsening of her injury that occurred during a vault performed during gymnastics practice. Upon initial evaluation, the patient was determined to have inadequate neuromuscular control to maintain a neutral patellofemoral during simple squatting tasks. After 4 weeks of physical therapy, the patient demonstrated the ability to perform depth jumps intended to simulate landing from various heights while maintaining patellofemoral neutral and without pain. However, when a cognitive task (word association) was added to the landing task, the patient immediately reverted to her pre-training movement pattern. The patient was seen for three more weeks with a focus placed on dual task training, specifically during landing tasks. Upon discharge, the patient demonstrated the ability to land with the desired patellofemoral position while attending to various cognitive tasks.

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