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Neuroplasticity Following Anterior Cruciate Ligament Injury: A Framework for Visual-Motor Training Approaches in Rehabilitation

Anterior cruciate ligament (ACL) rupture is a common activity-related knee injury that usually requires surgical reconstruction to restore knee stability and function.[140] The lifetime burden of ACL injury ranges from $7.6 to $17.7 billion per year in the United States.[96] Despite surgical reconstruction and physical rehabilitation, injury of the ACL dramatically increases the risk for costly and long-term disabling osteoarthritis, associated decreased lifelong physical activity, and decreased work productivity.[4,14,93,96] Importantly, reconstruction and rehabilitation that rely primarily on traditional neuromuscular interventions have a failure rate of up to 30% for rerupture after return to sport.[74,120,121,154] This high failure rate is further compounded by the inability of a majority of individuals to return to preinjury levels of activity.[10]

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, and give less consideration to cognitive or neurological components.[60,107,109,156] While rectifying the biomechanical profile and restoring muscle strength are vital components of the rehabilitation process, there may be potential to improve function and decrease reinjury risk.[58,99] Recent reports have found unresolved neuroplastic alterations after injury, reconstruction, and rehabilitation that may limit function and return to sports participation.[9,17,87,94] By targeting these neurologic factors and integrating neurocognition during neuromuscular rehabilitation progressions, it may be possible to improve the transfer of sensorimotor adaptations from the clinic to activity, and ultimately to improve patient outcomes.[16,61]

The training, and even restoration, of primarily biomechanical factors relative to ACL-injury risk[67,132] may not address all the physiologic consequences of injury, as patient-reported dysfunction and poor movement control may persist for years.[8,108,119,129,131,158] The impaired physical performance and patient-reported dysfunction might, in part, have a neurologic origin.[79,84,123] The capacity for neuroplasticity after injury and during therapy may present an opportunity to

SYNOPSIS: The neuroplastic effects of anterior cruciate ligament injury have recently become more evident, demonstrating underlying nervous system changes in addition to the expected mechanical alterations associated with injury. Interventions to mitigate these detrimental neuroplastic effects, along with the established biomechanical changes, need to be considered in the rehabilitation process and return-to-play progressions. This commentary establishes a link between dynamic movement mechanics, neurocognition, and visual processing regarding anterior cruciate ligament injury adaptations and injury risk. The proposed framework incorporates evidence from the disciplines of neuroscience, biomechanics, motor control, and psychology to support integrating neurocognitive and visual-motor approaches with traditional neuromuscular interventions during anterior cruciate ligament injury rehabilitation. Physical therapists, athletic trainers, strength coaches, and other health care and performance professionals can capitalize on this integration of sciences to utilize visual-training technologies and techniques to improve on already-established neuromuscular training methods.

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close the gap between rehabilitation and activity by targeting a broader spectrum of sensorimotor function during neuromuscular training.[58,64,108,109] Alternative approaches and adjunct therapies may help to address the neurological system functions associated with the faulty movement patterns underlying ACL reinjury risk.[18,87,94,121]

As an example, typical rehabilitative exercises are completed with an internal focus of control, meaning that full attention is directed to the internal aspects of the movement only (eg, avoidance of excessive knee valgus or increasing knee flexion).[20,155,156] 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. But, function in the athletic environment, or even in 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.[11,41,128]

The need to challenge a broad spectrum of sensorimotor control is demonstrated by the noncontact ACL-injury scenario: 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.[26,68,82,88] The need to bridge the intense neurocognitive and motor control demands of sport during rehabilitation may therefore benefit from specific interventions that target these neurocognitive factors in addition to the biomechanical techniques that are already widely addressed.

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.[26,68,82,88] In a constantly changing environment, the sensory system's 3 primary afferent pathways (vestibular, visual, and somatosensory) provide the complex and integrated information necessary for the efferent neuromuscular control system to maintain adequate stability and control.[95,153] One area of sensorimotor function that may uniquely be affected by ACL injury is motor control requiring visual feedback.[95] The visual system provides a fundamental mechanism for coordination, regulation, and control of movement while managing environmental interactions (external focus).[122,139,150] Visual feedback is especially needed in executing movement sequences[5,111] and increasing task complexity and variability.[40,89,128,150] The interplay between vision and somatosensation is particularly vital to provide sufficient afferent input to the central nervous system (CNS) to regulate motor control and to maintain neuromuscular integrity during action and environmental interaction.[133,134,143,149,153] 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).[23,95,133,143,150,153] Trauma to the ACL has been shown to modify how the nervous system processes these interactions between vision and somatosensation.[2,3,55,79,115] Targeting injury-induced sensory-motor plasticity presents a unique opportunity to improve the translation of neuromuscular system enhancements from the rehabilitation environment to the return-to-sport environment.[29,76,100] Thus, our purpose in this commentary is to highlight the contributions of nervous system function and reorganization in the ACL-injury rehabilitation process, and specifically how adding visual-motor approaches during neuromuscular training may mitigate potentially limiting factors during return to high-demand physical activities.

ACL Injury–Induced Sensory Visual-Motor Processing Compensations

To better understand the rationale for how visual-motor training may enhance ACL-injury rehabilitation, a thorough understanding of the current evidence on neuroplastic changes associated with ACL injury is required. The overarching concept 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 facilitate motor control adaptations. The reconstruction process leads to further deafferentation of the joint, causing continued neuroplastic modifications that result in maladapted efferent neuromuscular output (**FIGURE 1**).

CNS Adaptations

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, contributing to proprioceptive, nociceptive, and reflex function.[59,118] The initial sensorimotor neuroplasticity after ACL injury is likely caused by the abrupt loss of this connection, which once provided the nervous system with continuous feedback. In human studies, the afferent loss is demonstrated by altered or absent somatosensory-evoked potentials with stimulation of the common peroneal nerve[37,39,147,148] or the ACL directly.[125] The loss of primary afferent information combined with the pain and inflammatory response contribute to fundamentally alter the somatosensory feedback.[32,75,79,91] The disrupted input, combined with mechanical changes and compensations[110,131] (contralateral loading,[15,119] hip or ankle strategies[48,56]), facilitates the adaptations for motor control.[68,128,129] On a foundational level, altered motor output manifests in disrupted gamma motor neuron function[83,85,86] and perturbation reflexes,[38,44] which play a key role in the abil-

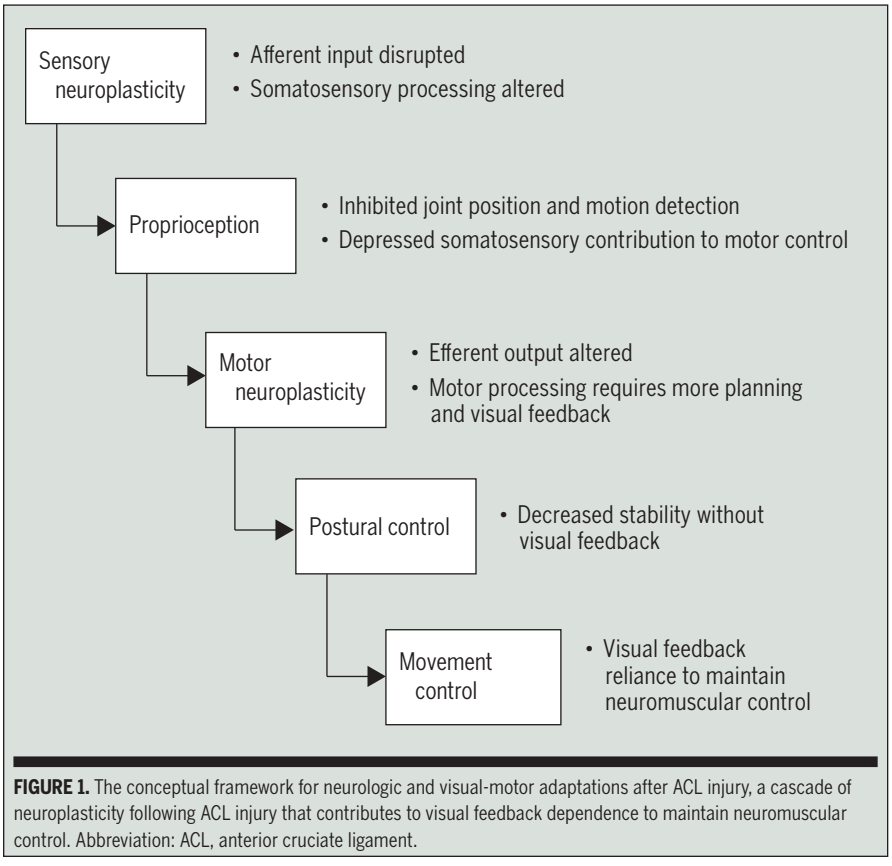

FIGURE 1. The conceptual framework for neurologic and visual-motor adaptations after ACL injury, a cascade of neuroplasticity following ACL injury that contributes to visual feedback dependence to maintain neuromuscular control. Abbreviation: ACL, anterior cruciate ligament.

ity to maintain neuromuscular integrity in a changing environment that requires rapid and precise muscle stiffness or activation strategies.[30,81,145] 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. As such, neuromuscular control after ACL injury may require enhanced visual feedback, 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 ACL reconstruction and may become even more pronounced and/or present bilaterally.[24,83,84,87,94,130,148] The bilateral motor control, reflex, and proprioceptive changes are theorized to be due to both spinal[59,118] and supraspinal[39,123] mechanisms.[124] This ongoing neuroplasticity and altered mechanical and biological function of the joint combine to reduce proprioception acuity as measured by joint position sense,[27,92] movement detection,[27,54] and force sense.[66] To investigate the neurologic adaptations of functional sensory loss, Baumeister et al[17,18] used electroencephalography during force- and joint-sense tasks and found that those with ACL reconstructions had greater brain activation in attentional and sensory areas. 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 ACL reconstruction as compared to controls.[17,18] These results indicate that the loss of the native ACL not only constitutes a mechanical instability but also a degree of nervous system deafferentation that is not rectified with reconstructive surgery and rehabilitation.[78]

This partial deafferentation is further illustrated by investigations utilizing transcranial magnetic stimulation to assess the CNS efferent pathway between the quadriceps and the brain.[65,90,113,123] Heroux and Tremblay[65] reported enhanced resting corticomotor excitability in those with ACL injury. A potential mechanism for increased resting motor cortex excitability may be due to the affected sensory feedback, as the brain attempts to maintain motor output with attenuated sensory input. This increase in excitability may increase potential feedforward mechanisms by decreasing the threshold for connections with motor planning areas, or allow for increased input from other sensory sources (vision, vestibular).[62,116,144,159] A recent neuroimaging investigation by Kapreli et al[79] provides further evidence of the neuroplastic effects of ACL injury. They performed functional magnetic resonance imaging of the brain during knee flexion and extension, and found that those with an ACL injury had increased activation of the presupplementary motor area, posterior secondary somatosensory area, and posterior inferior temporal gyrus compared to matched controls.[79] The presupplementary motor area is highly involved in complex motor planning,[12,111] and, despite the relative simplicity of the movement task (single-joint movement of 40° of knee flexion/extension while lying 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 may indicate that, on a neural control level, simple movements are more taxing to those with a previous ACL injury.[104] 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 is highly interconnected with the anterior secondary somatosensory area that integrates somatosensory inputs.[33,49,145] 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. Alternatively, the prolonged nature of the rehabilitation, chronic pain, or joint instability may continue to disrupt typical somatosensory-system afferent integration. The posterior inferior temporal gyrus plays a role during many cerebral functions,[25,28] but may primarily be involved with visual processing of movement.[122] As such, an increase in posterior inferior temporal gyrus 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.[37,39,55,79,147,148]

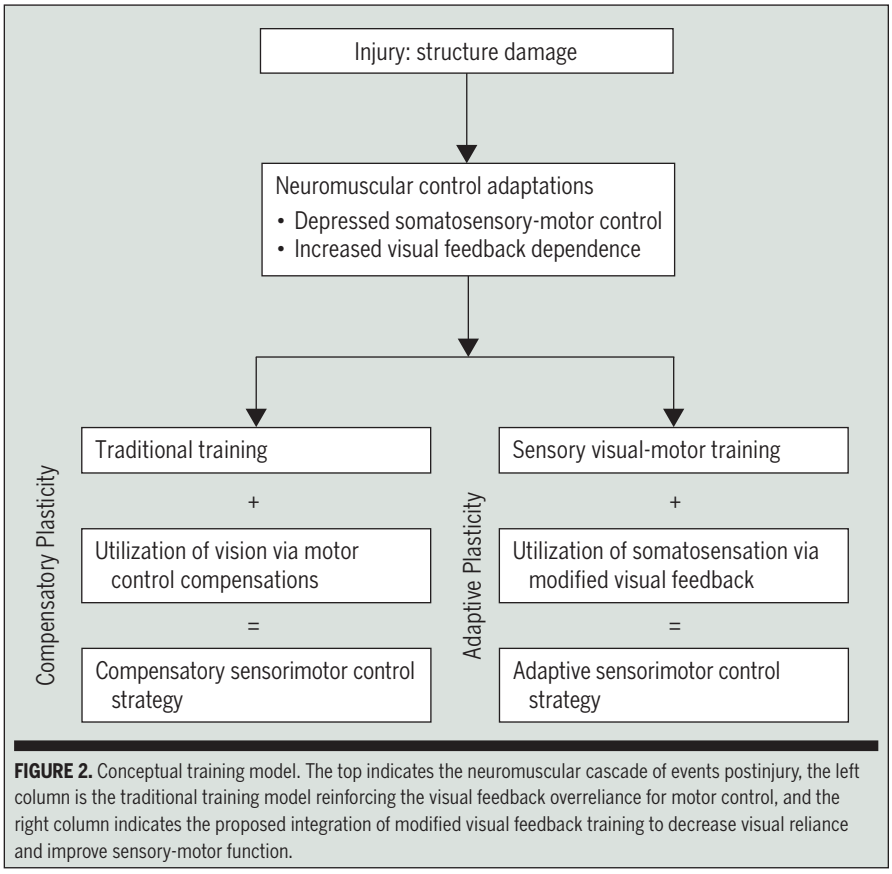

FIGURE 2. Conceptual training model. The top indicates the neuromuscular cascade of events postinjury, the left column is the traditional training model reinforcing the visual feedback overreliance for motor control, and the right column indicates the proposed integration of modified visual feedback training to decrease visual reliance and improve sensory-motor function.

Biomechanical Adaptations

These neuroplastic observations following ACL injury are further 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 in controls, possibly due to overload of motor planning resources.[73,112] 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),[114,115] but limited to no degradation in postural control with eyes open, as they are able to use vision to compensate and maintain balance.[69,97] 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.[102,103,142] The simple addition of a target during a jump-landing task increased injury risk mechanics[52] and altered muscle activation, decreasing postural stability.[152] The effects of forcing visual focus on the environment during more complex cutting or direction-change tasks further degrade neuromuscular control capability in healthy athletes with the addition of a defender,[102] a virtual soccer interface,[36] or a level of unanticipated decision making during the task (selecting direction).[101,126] The effect of occupying the visual system with environmental cues during landing or change of direction is even greater in those with a history of ACL injury.[72,73]

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 postinjury disrupted sensory feedback, combined with the observed motor compensations, contributes to fundamentally alter the CNS mechanisms for motor control.[1,17,18,80,94,147,148,160] 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 sensorimotor adaptations to decrease dependence on visual feedback when transitioning to more demanding activities.

Visual-Motor Training as a Rehabilitation Tool

Typically, neuromuscular interventions (eg, plyometrics, balance training, strengthening exercises) allow full focus of attention on the movement, whereas in sporting situations this is rarely the case.[88,98] Traumatic injuries (ACL ruptures) tend to occur during complex game situations when the player must

FIGURE 3. Strobe glasses. The bottom picture on the left is the opaque condition and on the right is the clear condition. These conditions continuously alternate, with potential for 8 settings, with the clear condition always lasting 100 milliseconds and the opaque conditions varying from 25 milliseconds to 900 milliseconds. The top picture provides an illustrative example of a first-person perspective with the glasses at a moderate level of occlusion (approximately level 5 or 6, with a 150- to 233-millisecond opaque interval).

manage multiple variables (eg, ball, players, field position, game strategy) requiring full visual attention to the environment, theoretically leaving less cognitive processing resources for neuromuscular control.[26,68,71,82,88,98] These environmental demands and the increased need for visual feedback for knee control in individuals after ACL injury[55,79,115] combine to create a higher-risk state for the athlete. This framework indicates a CNS alteration of afferent processing, to compensate for the lost somatosensory contribution by increasing utilization of visual resources for neuromuscular control, which may be an adaptation of the disrupted proprioceptive afferent input from the damaged ACL and associated noxious stimuli.[1,17,18,50,117] It is possible that after extensive time and/or training, a measure of motor function may be restored, but at the expense of compensations that allow the sensory deficits to remain.[2,53,57] Motor function may normalize with basic tasks in the clinic, such as hop or strength tests, but may not transfer to the demanding athletic environment, where the proprioceptive sensory loss may result in impaired motor function as the task and environmental complexities increase.[19,46,76,77] Currently used rehabilitative methods may even be further contributing to the neuromuscular control compensations and facilitating possible compensatory neuroplasticity (**FIGURE 2**).[17,18,65,79,83,87,129] Recognizing and addressing the specific postinjury neuroplasticity during neuromuscular training may provide an avenue for the clinician to address both the physical and neurocognitive demands of return to sport.[13,121,157]

This framework highlights 3 related sensorimotor adaptations occurring in the athlete with an ACL injury: (1) depressed or disrupted somatosensory input and altered sensorimotor processing, which induce (2) increased visual processing to plan movement and maintain neuromuscular control and (3) increased cortical top-down motor control strategies.

Modifying Visual Feedback

The need to transfer neuromuscular control strategies from the stable training environment to the chaotic athletic field requires that interventions integrate complex sensory inputs (environmental stimulus, visual and proprioceptive acuity) in conjunction with the motor outputs (strength, movement quality).[2,17,18,20,55,61] Disrupting visual feedback as an adjunct to traditional rehabilitation may more closely mimic actual activity demands via escalated load on the neurocognitive system[36,52,98,102,152] and smooth the transition back to activity by providing a closer analog to the inherent environmental challenges of sport.[95,98] Historically, the primary method to disrupt the visual feedback system has been to use complete visual obstruction (eyes closed or blindfold). This kind of visual deprivation presents a motor control challenge in a healthy population[133] and has a more pronounced effect in individuals with an ACL injury.[55,115] However, rehabilitation using eyes-closed or blindfolded conditions[55] has been restricted to static balance,[115] proprioceptive,[55] or simplified single-movement[34,133] tasks. The influence of modifying the visual input by any means (ball, defender, blindfold, target, visual signals) during more challenging dynamic tasks, such as rapid direction change or jump landing, has an even greater effect on neuromuscular control.[34,36,52,133,152]

Direct Visual Disruption

Ideally, inhibiting visual input during these dynamic, more athletic maneuvers would provide a means to directly address the compensatory neuroplastic sequelae after ACL injury and train the neuromuscular system in a functional manner. A recent technological innovation has made this possible by decreasing visual input without fully removing it.[21,22] This tool, stroboscopic eyewear (eg, PLATO Visual Occlusion Spectacles [Translucent Technologies Inc, Toronto, Canada], Nike SPARQ Vapor Strobes [Nike Inc, Beaverton, OR], PRIMARY Strobe Glasses [Appreciate Co, Ltd, Kyoto, Japan]) (**FIGURE 3**), has the ability to partially obstruct vision by intermittently switching from clear to opaque, allowing highly complex, dynamic athletic maneuvers to be performed under degraded visual input (**FIGURE 4**).[6,21,22,106] Practice with a stroboscopic vision system has already been shown to enhance aspects of basic visual cognition, such as tran-

Exercise	
Single-leg hop with air target, unstable landing and reaction ball Stand on 1 leg, jump forward, contact air target in flight with opposite hand of jump-landing leg; on landing, catch ball. Shown with Vertec target at 50% of maximum jump height	
Broad jump with reaction ball and unanticipated cut Stand on both feet, jump out, land on both feet, and track the ball to determine cut direction. Progress to decrease anticipation time from landing to ball release and cut direction	
Single leg, air target, and reaction ball Stand on both feet with knees slightly bent, then jump and rotate 180° while in the air. The opposite hand of the landing foot reaches out to contact a target. When landing, catch the ball. Shown with Vertec target at 50% of maximum jump height	

FIGURE 4. Examples of higher-level, dynamic neuromuscular training exercises incorporating visual target acquisition, environmental interaction, anticipatory ability, unstable surfaces, and stroboscopic visual interference, using stroboscopic glasses.

sient attention,[7] anticipatory trajectory estimation,[138] and short-term memory.[6] These abilities may play a role in mitigating or avoiding injurious collisions or situations via improved anticipation and processing speed,[63] which in turn may modify ACL-injury risk.[141] Training with intermittent visual input also offers a simple, easy-to-implement, and novel stress to the neural control system that is compatible with current neuromuscular training exercises. The disrupted visual feedback may more closely simulate the neurocognitive demands of activity in the safety of a controlled clinic or field environment under the supervision of a qualified professional. Such stroboscopic visual training can also be tailored to fit a desired difficulty level by altering the rate of stroboscopic interruption (ratio of opaque versus transparent status). This adjustability is an important feature because postinjury, visual interference could increase reinjury risk during rehabilitation, particularly if the athlete has not yet adapted to the depressed visual feedback. The ability to scale the level of interference up or down provides a means for the clinician to progress the patient, based on clinical judgment. Also, a warm-up period is recommended to allow patients to familiarize themselves with the visual effect by doing less aggressive movements, such as single-leg balance or upper extremity exercises (ball toss), before advancing to jump-landing or direction-change tasks. The eyewear is also wireless and portable, making for flexible implementation in a wide assortment of clinics or on-field progressions of already-established neuromuscular training exercises.[107]

After injury, the CNS experiences a compensatory overutilization of visual feedback to maintain neuromuscular control. The suggested intermittent visual training can decrease the available visual feedback to the CNS. This may force the CNS to engage in an adaptive strategy by increased weighting of the remaining proprioceptive inputs, as opposed to continuing to compensate with visual feedback (**FIGURE 2**). The neural mechanisms underlying this sensory visual-motor interaction are theoretical at this point, but may include increased utilization or efficiency of the remaining proprioceptive or vestibular inputs, and/or improved visual-motor processing efficiency to make up for the increased demand. Alternatively, intermittent visual training could lead to increased attentional focus[70] and/or changes in the rate of memory consoli-

dation[6] that, in turn, improve the use of afferent information for guiding motor control. Regardless of the mechanism, this training may improve the transition to athletic activity by decreasing dependence on vision to maintain dynamic motor control, allowing its use for environmental interaction on return to the complex athletic environment.

Indirect Visual Distraction

Other techniques to modify visual feedback outside of stroboscopic eyewear may be more accessible and still provide a means to encourage adaptive neuroplasticity. Progressively increasing the difficulty of the sensorimotor challenge can not only facilitate neuroplasticity for motor control, but also improve sensory integration and address the visual processing bias. The key considerations to completing the latter are the focus of attention, task complexity, visual input, and cognitive load during rehabilitation.[29,126] Many mechanisms, such as incorporating reaction-time components,[126] ball tracking, engaging other players,[102] adding decision-making[29] or anticipatory aspects,[126] and having the patient dual task[112] by engaging the upper extremity while performing lower extremity exercises or occupying the mind with memory or related tasks, can increase the neural demand of neuromuscular training strategies. Recently, Negahban et al[112] used a classic dual-task paradigm by having individuals post–ACL reconstruction maintain single-leg postural control while performing a cognitive task (holding a string of numbers in mind). This additional demand degraded postural stability in the ACL cohort but had little effect in control participants. This builds on previous work that has established that adding environmental interactions, such as a target, another player, a ball, or decision making, has greater influence in those with ACL injury.[42,73,151] Consequently, strategies to address these performance deficits should be incorporated in neuromuscular training targeting the transition from clinic to activity.

Visual-Motor Training

Stroboscopic training, dual tasking using environmental interaction or adding visual obstruction, and facilitating motor learning are methods to decrease visual feedback during established exercises to make vision a less salient form of information for motor programming. These strategies may stimulate the CNS to reweight information from the somatosensory and vestibular inputs to decrease excessive reliance on visual feedback. An alternative to reducing visual feedback dependence is to make the visual processing system more efficient and able to handle the increased demand. The injury may only allow so much sensory adaptation, and a degree of increased visual feedback may have to be regulated to maintain neuromuscular integrity during action, regardless of how much we attempt to force proprioceptor or vestibular upregulation. In this case, visual training in isolation or in combination with neuromuscular training methods may provide a means to further address the compensatory neuroplasticity following injury. Visual training has been shown to enhance sport performance[35,106] and improve reaction time and visual processing ability.[6,7,138] Simply increasing these fundamental neurocognitive attributes may allow the athlete to handle the dual task of maintaining knee control while interacting with the environment and responding to potentially injurious situations.

Many methods for training the visual system exist, and each one tends to focus on a different visual construct. These constructs include occulomotor control, multiple-object tracking, visual sensitivity, spatial attention, visual memory, reaction time, and processing speed. Several commercial tools exist that target 1 or more of these visual processing attributes. These tools range in cost and approach, from high-level computer-based systems, such as CogniSens (CogniSens Inc, Montreal, Canada), Dynavision (Dynavision International LLC, West Chester, OH), and the SPARQ Sensory Training Station (Nike, Inc), to web-based applications, to simple paper or object manipulation.[35,47] Software or full electronic station setups are ideal and the literature supports their ability to increase performance metrics in athletes, but the clinician may not have access to this type of technology. Alternative mechanisms to train the visual system with minimal equipment include the use of a tachistoscope (flash cards of objects/numbers/letters of increasing value that must be attended to and recalled) to improve object recognition in the visual field, a Brock string (string of colored balls at different distances held to the face; the participant must focus on each one in sequence) to improve occulomotor muscle capacity to focus on targets rapidly, and saccades (charts of random letters on a wall; the player must focus on each one and call out letters in sequence) to improve rapid visual processing.

Motor Learning Applications

The increased level of cortical drive during movement, seen in individuals with an ACL injury, provides a neurological mechanism[18,65,79] to explain the greater amount of cocontraction and muscle-guarding strategies seen after injury.[146] Such a neuromuscular control strategy is consistent with an increase in internal focus of control, likely due to the increased conscious awareness of the injured joint and its movement as opposed to attention to the external environment.[58,155] Rehabilitation guidelines that focus on explicit feedback (eg, contract quadriceps or keep knees over your toes) might be further promoting the top-down cortical and visual feedback control of the movement, as opposed to facilitating a return to a more autonomic somatosensory feedback control and visual feedback on the environment. As discussed earlier, the increased activation of the presupplementary motor area to perform a simple knee joint movement[79] further demonstrates the increased need for cortical motor planning of movement after ACL injury. The implications of these findings are concerning for return to sport, as the

demands of complex, more dynamic motion may exceed the capability of the region to program optimal movement and may contribute to injury risk.

The classic mechanism to rectify increased reliance on cortical mechanisms for lower extremity control is to advance patients to the autonomous stage of motor learning.[95] In early-stage rehabilitation, explicit focus is needed to restore muscle function, and internally focused feedback such as "contract your quad," "knees over the toes," or "bend your knee" is commonly used. Advancing rehabilitative feedback to an external focus, such as "land on the markers" or "touch the target as you land," will facilitate transfer of motor control to subcortical regions and free cortical resources for programming more complex motor actions.[58,127,137] Such motor learning principles applied to neuromuscular training may assist in transferring knee control strategies to the athletic field when conscious attention is being paid to the environment and not knee position.[127,136] The additions to neuromuscular training previously discussed can also help speed the process of acquiring the ability to transfer motor skills to the field.

Limitations

The framework described above provides an opportunity to develop hypothesis-driven clinical and research constructs for further exploration. Prior to steadfast clinical recommendations, rigorous longitudinal and controlled trials should be undertaken; however, exploration of novel neuromuscular re-education techniques may provide immediate enhancement to current rehabilitation and prevention methods. We have suggested some methods to address the postinjury neuroplasticity during the rehabilitation process, and, undoubtedly, clinicians and researchers will develop more novel and applicable methods in the near future. There is insufficient evidence to recommend one method or system over any other at this time, but we encourage clinicians to consider visual-motor function on any level as a part of ACL rehabilitation and injury prevention programs. Implementation can be as basic as adding an eyes-closed or a cognitive dual task during quadriceps contraction sets as the patient progresses toward the autonomous stage in that exercise during the first few clinic visits, or including environmental stimuli (other players, unanticipated direction changes, target acquisition, or reaction ball) during functional tasks later in rehabilitation, and can advance to highly complex virtual reality simulations that are increasing in quality and accessibility.[43,51] Collectively, these vision-based interventions are gaining widespread use in a number of clinical (eg, concussion, cognitive disorders) and nonclinical (eg, entertainment, performance enhancement, military) applications, and future integration with musculoskeletal injury rehabilitation may create an entirely new avenue for improving neuromuscular function to prevent and treat orthopaedic injuries.

Visual-Motor Training in Primary ACL Injury Prevention

The presented evidence suggests that ACL injury can alter the nervous system utilization of somatosensory input, afferent integration, and motor output. These neuroplastic effects induce a neuromuscular control strategy that increases dependence on visual feedback to regulate dynamic stability of the system. However, some of the described postinjury adaptations may actually be present prior to injury, potentially playing a role in primary ACL risk. Swanik et al[141] reported initial findings of decreased visual processing capabilities in individuals prior to ACL injury. Using neurocognitive testing, they found that a decrease in visual processing speed and reaction time was predictive of subsequent ACL injury.[141] A theorized mechanism for visual function influencing injury risk is in the ability to prepare the neuromuscular system in anticipation of high-risk situations, maneuvers, or incoming players.[63,105] If visual processing resources are taxed to maintain the afferent input for knee motor control, this may decrease the ability to compensate for environmental stimuli and attenuate unanticipated maneuvers, such as cutting or landing, that depend on quick visual processing.[31,72,102] Future studies should investigate the potential association of varying visual processing capabilities and sensorimotor neural integration with musculoskeletal risk, in addition to investigating visual feedback modification or visual-motor additions to neuromuscular training in relation to injury prevention.

CONCLUSION

This review highlights a conceptual framework for integrating a variety of visual-motor constructs during neuromuscular rehabilitation as a future avenue of research to optimize musculoskeletal therapy interventions. A strength of these recommendations is that they act as adjunct strategies to foundational neuromuscular techniques for optimizing strength, multiplanar knee and trunk control, and movement asymmetries.[45] These suggestions provide an opportunity to supplement more traditional interventions by further targeting neuroplastic, cognitive, and visual-motor capabilities. The clinician can approximate the neurocognitive demands of higher-intensity athletic activity in a safe, controlled, and—most importantly—feedback-rich environment under the supervision of a well-trained professional before reintegration into sport. Recognition of the visual-motor implications of neuromuscular control and injury recovery and prevention, combined with new technologies and approaches, may help to mitigate postinjury movement dysfunction and decrease injury risk when returning to activity.

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