Clinical Commentary/Current Concept Review

Visual Perturbation to Enhance Return to Sport Rehabilitation after Anterior Cruciate Ligament Injury: A Clinical Commentary

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Anterior cruciate ligament (ACL) tears are common traumatic knee injuries causing joint instability, quadriceps muscle weakness and impaired motor coordination. The neuromuscular consequences of injury are not limited to the joint and surrounding musculature, but may modulate central nervous system reorganization. Neuroimaging data suggest patients with ACL injuries may require greater levels of visual-motor and neurocognitive processing activity to sustain lower limb control relative to healthy matched counterparts. Therapy currently fails to adequately address these nuanced consequences of ACL injury, which likely contributes to impaired neuromuscular control when visually or cognitively challenged and high rates of re-injury. This gap in rehabilitation may be filled by visual perturbation training, which may reweight sensory neural processing toward proprioception and reduce the dependency on vision to perform lower extremity motor tasks and/or increase visuomotor processing efficiency. This clinical commentary details a novel approach to supplement the current standard of care for ACL injury by incorporating stroboscopic glasses with key motor learning principles customized to target visual and cognitive dependence for motor control after ACL injury.

Level of Evidence

5

INTRODUCTION

Anterior cruciate ligament (ACL) tears are common orthopedic injuries,[1] involving an extensive plan of care and physical therapy following surgical reconstruction.[2] Despite receiving comprehensive approaches to restore knee function, quadriceps strength,[3,4] and joint stability,[5–7] re-injury rates remain high, especially among young female athletes.[4,8–17] This increased risk of re-injury may stem from nuanced neuromuscular consequences of ACL injury that therapy may not adequately address.

While ACL tears are peripheral joint injuries, the combination of effusion, pain, mechanical instability and deafferentation secondary to loss of joint mechanoreceptors may modulate central nervous system (CNS) reorganiza-tion.[18,19] The CNS reorganization manifests as proprioceptive deficits and impaired motor coordination secondary to increased attentional, cognitive[20–23] and visual relative to proprioceptive processing demands for motor control.[20–35] A potential avenue to augment ACL rehabilitation is to facilitate sensory reweighting (nervous system adjustment of relative sensory input/processing for motor control) by shifting the post-injury reliance on vision for motor control to remaining proprioceptive inputs (e.g., the joint capsule, other ligaments, muscle spindles). Specifically, the use of visual perturbation training, which aims to reduce visual input availability during standard rehabilitative exercises, may reduce the dependency on vision and reweight neural processing toward proprioception and/or increase visuomotor processing efficiency.[36] Additionally, the application of

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key motor learning principles may support visual perturbation training, such as 1) an external *visual* focus of attention or cueing to help ensure visuospatial demands during training and 2) implicit learning to reduce the cognitive requirements for motor control and promote movement automaticity.[37–40] The following commentary details an example of a sensory reweighting protocol that combines the use of stroboscopic glasses and key motor learning principles.

BEHAVIORAL SUPPORT FOR INCREASED VISUAL RELIANCE & NEUROCOGNITIVE MOTOR PLANNING FOLLOWING ACL INJURY

INCREASED VISUAL RELIANCE

A series of investigations in ACL deficient (ACL-D) and reconstructed (ACL-R) patients provide support for increased visual reliance for motor control.[26–35] During postural control tasks, patients with ACL injuries and uninjured controls performed similarly when vision was unobstructed.[31,32] However, when vision was perturbed, patients with ACL injuries performed significantly worse (e.g., increased postural sway, failure in task completion).[28,30,33–35] While a recent meta-analysis indicated patients with ACL-R are not as dependent on vision for postural control as patients with ACL-D,[41] the mixed finding may be secondary to not challenging knee control during single-leg stance (by allowing a straight leg position), static postural control not being sufficiently challenging in those with reconstruction or complete vision obstruction not perturbating visuospatial processing sufficiently to elicit a deficit. This is exemplified by patients with ACL-R being more affected by visual perturbation (i.e., stroboscopic glasses) during drop landing and the transition from double to single leg stance with eyes closed and when challenged with visuocognitive tasks relative to matched controls.[27,34,42]

An increased weighting towards visual input and processing for postural and lower extremity motor control following ACL injury may emerge from a sensory reweighting phenomenon that is driven, in part, by insult to the underlying joint tissue and ligament mechanoreceptors.[25] These mechanoreceptors, including Ruffini and Pacinian corpuscles, provide information about joint position, motion and acceleration, and their loss compromises proprioception and functional stability.[43–46] Consequently, the CNS may employ functional strategies, such as sensory reweighting to more reliable stimuli (e.g., vision, vestibular), or increase cognitive and attentional processes to maintain adequate motor control.[36,47–51] The Bayesian optimal integration model details how weighting sensory stimuli by reliability reduces the uncertainty of perception, thereby optimizing performance.[52–54] Further, physical therapy following ACL injury may also increase visual attention to the knee, as clinicians primarily utilize visually-dominated exercises and provide feedback with an internal focus of attention (i.e., emphasizing movement kinematics or muscle activation, rather than movement actions) to the injured joint.[37,55–59] However, weighting vision to guide lower limb movement may be maladaptive for athletes returning to a competitive sport environment, where the high demand to integrate dynamic visual information may limit the CNS's capacity to allocate neural resources to guide movement. Therefore, patients with ACL injuries may benefit from therapeutic interventions that encourage sensory reweighting from vision towards proprioception for motor control.

INCREASED NEUROCOGNITIVE MOTOR PLANNING

Excessive knee valgus has been identified as a major risk factor for primary and secondary ACL injury, with high sensitivity (78%) and specificity (73%).[60] Herman and Barth identified a significant relationship between baseline neurocognition and knee valgus motion, where those with lower visual-memory and neurocognitive ability demonstrate increased knee valgus motion during a drop-landing task involving an unanticipated rebound immediately after landing.[61] These studies suggest an athlete's baseline neurocognitive function may contribute to his or her risk of injury.[60,61] A common therapeutic modality used to target neurocognitive function is dual-tasking, which involves the completion of two or more tasks simultaneously (e.g., balancing on one leg while counting down from 1,000 by 7).[62] For example, patients with ACL injuries exhibit higher dual task-related costs during postural stability, gait and balance tasks.[23,63–66] Taken together, following ACL injury, patients may experience a reduced capability to simultaneously engage in cognitive processing and motor performance. Neural mechanisms for this deficit may be secondary to the disruption of typical ACL afferent information utilized by the primary motor cortex, which may result in increased frontal activity (e.g., presupplementary motor area, supplementary motor area) to compensate.[21,67,68] Thus, the cognitive demands of sport may exceed the patient's capability to optimally attend to external visual stimuli (e.g., opponents, balls) and maintain low injury-risk biomechanics.

NEUROIMAGING INVESTIGATIONS FOLLOWING ACL INJURY

ACL INJURY ASSOCIATED VISUOMOTOR & VISUOSPATIAL BRAIN ACTIVATION

Cross-sectional studies using functional magnetic resonance imaging (fMRI) have assessed neural activation differences for knee motor control in patients with ACL-D and ACL-R compared to uninjured, matched controls.[20,21,69,70] In patients with ACL-D ~two years post-injury, fMRI identified increased activation in the posterior inferior temporal gyrus during a unilateral knee flexion/extension task.[69] The posterior inferior temporal gyrus has been implicated in the recognition of biological movements, such as gait-like motion, rather than random motion.[71] For patients with ACL-R ~3 years post-surgery, fMRI further identified increased neural activity within the lingual gyrus for both knee and combined hip-knee coordinated movements.[70,72] The lingual gyrus is involved in the cross-modal integration of congruent visual and tactile stimuli in a spatially-specific manner.[73,74] Increased neural activity requirements for the posterior inferior temporal gyrus and lingual gyrus corroborate the behavioral investigations, indicating an increased reliance or shift in visual information processing during

motor control following ACL injury.

ACL INJURY ASSOCIATED NEUROCOGNITIVE MOTOR PLANNING BRAIN ACTIVATION

Other regions with increased neural activity include the presupplementary motor area in patients with ACL-D ~two years after injury as well as the frontal gyri, inferior frontal pole, paracingulate gyrus and anterior cingulate gyrus for patients with ACL-R ~five years post-surgery.[22,69] While both injured populations performed identical tasks, differences in neural activation patterns are likely attributed to demographic (high vs. low functioning patients, activity level), surgical, time from injury, and rehabilitation protocol differences. Increased activation of the presupplementary motor area in patients with ACL-D may reflect increased cortical activity for planning simple movements.[69] Increased activation across the frontal lobe in regions responsible for motor control further supports the hypothesis that patients with ACL injuries utilize increased cognitive resources for motor control by engaging in less efficient neural activation strategies.[22] Neural efficiency refers to the reduced neural activity requirements of experts to perform a learned skill or task relative to novices, suggesting relative magnitude of neural activity scales with expertise and the ability to handle more complex coordination or environmental perturbations.[75–78]

The lack of neural efficiency and associated frontal region activity is corroborated with electroencephalography (EEG), indicating increased frontal theta power during force control and joint position tasks in patients with ACL-R ~one year post-surgery compared to uninjured controls.[20,21] Frontal Theta power is an indicator of focused attention and task complexity,[20] which may indicate that simple knee force control and joint position tasks are more complex and require greater attention for patients with ACL-R. Additionally, EEG has revealed that patients with ACL-D require more cognition/attention resources relative to healthy controls during walking, running and landing tasks as evidenced by significant increases in delta, theta, alpha, and beta band power, as well as asymmetry of the beta band power across the frontal and parietal lobes during jogging and landing.[79] Increased activation across the frontal lobe, presupplementary motor area, increased frontal theta power during joint position sense and force matching tasks and increased cognition/attention during walking, jogging and landing support the behavioral data indicating increased neurocognitive motor planning neural activity following ACL injury. Taken together, patients with ACL injuries may experience a loss of neural efficiency to engage in motor control, thereby contributing to both 1) impaired motor performance during dual-tasking or unanticipated movements and 2) an increased risk of secondary injury when attempting to rapidly increase motor complexity and environmental stimuli during early return to sport.[23,63–66,80–82]

SENSORY REWEIGHTING THERAPY

VISUAL PERTURBATION TRAINING

Functional navigation and interaction with the environment rely heavily upon continual integration of visual information.[71,83,84] Visual information processing is further recruited for motor control following ACL injury, potentially due to sensory reweighting from the deafferentation of joint mechanoreceptors and/or the use of visually-dominated exercises and internal feedback to the injured joint during physical therapy.[36,37,55–59] While patients may be able to compensate with increased visual processing for simple exercises, an inundation of dynamic visual information on the sporting field may overwhelm neural processing resources and the visually biased movement compensation strategy may become a re-injury risk liability. ACL rehabilitation efforts may consider incorporating complex sensory challenges, like visual perturbation, in order to simulate the dynamic sport environment that athletes will face once they leave the clinic.[20,21,29,85–87]

Stroboscopic glasses (SG) provide a novel approach to train visuomotor function by perturbating and reducing visual feedback.[36] Typically, visual perturbation training has been limited to eyes open and eyes closed conditions with no progression between, but SG provides the ability to incrementally perturb visual information by increasing the duration of the opaque state (range: 25 to 900 msec) relative to the constant duration of the transparent state (100 msec).[88] Originally designed to be a mobile sports training tool, SG has allowed researchers to investigate the effects of perturbed vision in context-specific environments.[89] Early research with SG explored behavioral performance on motion coherence, divided attention, multiple-object tracking,[90] short-term visual memory,[91] and anticipation,[92] as well as performance on sports-specific tasks from single-leg squatting,[93] ice hockey,[94] tennis,[95] and badminton.[96] These authors concluded visual perturbation training improves sport-specific behavioral performance and aspects of neurocognition including visual memory, anticipatory timing of moving visual stimuli, and central visual field motion sensitivity and transient attention ability.

SG simulates the dynamic visuomotor and cognitive/attentional demands of athletic activity while remaining in a controlled clinical environment.[92,94,97,98] As patients with ACL injuries exhibit degraded motor control during drop-jump landing, cutting, and postural control under impaired visual conditions relative to normal vision,[27,28,30,33–35,99,100] SG may facilitate increased proprioceptive integration in response to perturbed visuospatial information.[36,89] ACL rehabilitation efforts that incorporate SG may be able to alter sensory weighting by decreasing the amount of visual information available to the athlete, thereby requiring the athlete to upregulate their use of remaining proprioceptive or vestibular inputs to guide movement. Utilizing SG in ACL rehabilitation may also enhance visuomotor processing efficiency in a compensatory manner to handle the increased reliance on vision to maintain low injury-risk biomechanics.[48]

MOTOR LEARNING PRINCIPLES

A key limitation of ACL rehabilitation is the inability to facilitate the acquisition of injury-resistant motor patterns that persist beyond the clinic.[101] This limitation likely contributes to high rates of secondary injury and long-term

pathologic sequalae, such as aberrant joint loading and early-onset osteoarthritis.[102] The incorporation of motor learning principles may facilitate the acquisition of lasting, injury-resistant movement patterns that persist beyond the clinic and into the field,[103] since these principles can facilitate neuroplasticity in cortical regions dedicated to movement.[104,105] Specifically, the use of an external focus of attention and implicit learning may serve an adjunctive role to sensory reweighting therapy. An external *visual* focus of attention can ensure visuospatial demands during training and implicit learning can reduce the cognitive demands for motor control to potentially enhance training.[37–40]

I. MODIFIED EXTERNAL FOCUS OF ATTENTION FOR VISUOSPATIAL ATTENTION

While the classic definition of external focus (EF) feedback is purely an attentional manipulation, this clinical commentary modified the traditional EF framework to push attentional focus toward the external visuospatial environment. ACL therapy that employs a *visual* EF can simulate real-world training scenarios that better prepare athletes for return to activity when visual attention is focused on the environment and not the body. Training with EF prioritizes the movement goal or the movement's effect on the environment, rather than an internal focus (IF) on the movement or body segment itself.[106] For example, a therapist who directs patients to balance a light-weight bar horizontally with their outstretched arm while performing a single-leg balance task employs visual EF.[37,107] In contrast, a therapist who directs patients to actively attend to their ankle, knee and hip alignment while balancing employs IF, which is the predominant strategy in ACL therapy. An IF approach to therapy may hinder the translational benefits of rehabilitation, as humans typically navigate the world with a visual EF on the environment (e.g., running to a ball) – not on their moving joints or mechanics.[108]

The Constrained Action Hypothesis posits conscious (cortical) awareness of movement constrains the automatic, subcortical processes that would otherwise facilitate movement.[109] By training with EF, one may relieve the attentional demands on the cortex by shifting motor control to subcortical regions and enhance motor learning and performance relative to training with IF.[102,110–113] Behaviorally, training with EF improves agility performance,[57] increases jump height,[114] and promotes safer landing patterns during a single-leg hop for distance task in patients with ACL-R compared to performance with IF.[115] Additionally, engaging in EF increases time to failure, reduces ratings of perceived exertion,[116,117] and increases movement efficiency potentially by reducing unnecessary muscle contributions by modulating the inhibitory mechanisms within the primary motor cortex.[117,118]

II. IMPLICIT LEARNING

Developmentally, humans learn to move through observation and implicit trial-and-error (e.g., learning to ride a bike, walk, throw).[119] Implicit feedback facilitates motor learning without explicit, declarative instructions or cuing,[37] thereby increasing neural efficiency by reducing the attentional demands to engage in complex movement. While explicit cuing engages cognitive processes (frontoparietal regions), implicit cuing facilitates more direct sensorimotor activity.[120] Further, training with implicit cuing has recently been associated with motor cortex reorganization, potentially supporting more efficient premotor or cortical interneuron processes.[121] While few studies have examined the behavioral impacts of implicit cues for sports medicine, Popovic et al. demonstrated improved landing biomechanics with implicit feedback relative to explicit/no feedback.[40] Thus, instructional language informed by implicit learning may augment visual perturbation training by modulating sensorimotor neural activity and potentially increasing neural efficiency by reducing the cognitive load of learning injury-resistant movement strategies. The newly freed cortical resources may enable athletes to more readily attend to visual distractors during high-level sport (e.g., the ball, opponents) while maintaining neuromuscular control.[37,122]

For example, consider the scenario where a therapist trains an athlete with an ACL injury to land correctly after a drop vertical jump. A therapist may opt to follow an explicit learning model and inform the athlete of all the biomechanical variables he or she is evaluating (e.g., trunk flexion, knee flexion, knee valgus, foot rotation, etc.). This type of learning requires the athlete to attend to multiple aspects of his or her landing mechanics, thereby occupying a substantial amount of his or her cognitive resources. However, a therapist who opts-in to implicit learning may instead provide metaphorical instructional language (e.g., "land like a feather") and simple "yes/no" or "good/bad" feedback to train the athlete to land. This trial-and-error method may augment visual perturbation training by alleviating the burden of attending to biomechanical variables, thereby freeing the athlete's cognitive resources to attend to external visual stimuli without compromising their neuromuscular control.

CLINICAL APPLICATION

Future studies are needed to explore the therapeutic efficacy of combining SG and motor learning principles (i.e., EF, implicit learning) with traditional therapeutic exercises during ACL rehabilitation. A barrier to such studies is a lack of clearly defined and easily replicable exercises that combine these novel modalities. This clinical commentary details ways therapists and researchers can supplement the current standard of care by adding SG and motor learning principles to agility, balance and plyometric exercises in novel ways. Provided are example exercises with specific instructional language and visual targets (Table 1). Further clinical examples of EF and implicit learning can be found in the work of Gokeler et al.[37] An error scoring system with detailed criteria to assess behavioral performance while wearing SG is provided as well (Table 2).

AGILITY DRILLS

(1) The T-test requires the athlete to run 10 m to tap a cone, cut to the right or left for 5 m to tap another cone, cut to the opposite direction for 10 m to tap the third cone, re-

Table 1: Instrumentation and Instruction to Facilitate Perception-Action that Employs Visual External Focus and Implicit Learning Principles.

Exercise	Visual Cues	Implicit Cues
T-test	Tap the cones	"Run as fast as a cheetah"
Agility Ladder Drills	The confines of the ladder	"The floor is as hot as lava"
Single-leg Deadlifts	Place an object by the cone(s)	"Flow like water"
Single-leg Stance (on foam)	Hold the bar horizontally	"Be steady as a rock"
Vertical Jumps	Hit the overhead target	"Explode like a volcano"
Squat Jumps	Land facing the cones	"Jump like a kangaroo"

Table 2: Error Scoring System Used to Assess Behavioral Performance.

Exercise	Error Count
T-test	1. Miss a cone 2. Cut to the wrong direction
Agility Ladder Drills	1. Hit the ladder 2. Incorrect foot placement
Single-leg Deadlifts	1. Opposite foot touches ground 2. Either hand touches ground 3. Object placed in wrong location
Single-leg Stance (on foam)	1. Opposite foot touches ground 2. Either hand touches ground
Vertical Jumps	1. Miss the target 2. Land on wrong foot
Squat Jumps	1. Land facing wrong orientation

turn to the center by cutting 5 m to tap the first cone and then run 10 m back to the start position - thereby running in a "T" formation (Figure 1A). A modification that increases the difficulty of this task and simulates the cognitive demands of sport is to have the clinician call out "Left" or "Right" to indicate which direction the athlete should cut prior to reaching the first cone, thereby creating an unanticipated cutting task which has been previously associated with increased injury-risk biomechanics compared to anticipated trials.[123] (2) Agility ladder drills require athletes to match specified foot-placement patterns within the context of an agility ladder (Figure 1B).

BALANCE

(1) Single-leg deadlifts may be modified by requiring athletes to gently place a small object on the ground next to a cone target (Figure 1C). To increase the difficulty, multiple cones can be placed at different angles within the athlete's field-of-view, set at distances equal to his or her max volitional reaching distance while standing on one leg. For example, if the clinician chooses to use three targets, then he or she may call out "Left," "Center," or "Right" to vary the task order and difficulty. (2) Single-leg stance on a foam surface may be modified by having the participant hold a light-weight bar with an outstretched arm and focus on keeping it steadily horizontal (Figure 1D).

PLYOMETRICS

(1) The VERTEC is a therapeutic tool that assesses maximum vertical jump height by requiring athletes to jump and hit an overhead target (Figure 1E). While using the VERTEC to have athletes hit a mark equal to 80% of their maximal jump height, clinicians may call out "Left" or "Right" during the initial flight phase of the jump to signal to the athlete to unilaterally land on his or her left or right leg.[124,125] The use of spontaneous cuing creates an unanticipated landing task, which has been previously associated with increased injury-risk biomechanics compared to anticipated land-
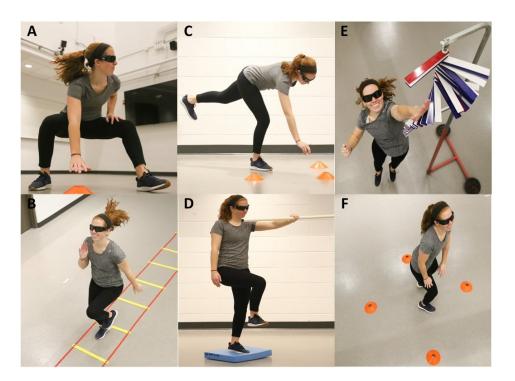
Figure 1: Exercise examples with clinical applications: (A) T-test, (B) Agility ladder drills, (C) Single-leg deadlifts, (D) Single-leg stance (on foam), (E) Vertical jumps, and (F) Squat jumps.

ing.[126] (2) Jump squats may be modified by placing four cones around the participant at 0, 90, 180 and 270 degree positions (Figure 1F). After numbering each cone one through four, the clinician may then rapidly call out cues to the athlete to specify which cone they should face after each jump squat. To increase the difficulty of this cognitive challenge, the clinician can introduce more cones or increase the rapidity of cuing.

SG LEVEL

Clinicians should first verify their athlete can perform all exercises successfully before incorporating SG. Then clinicians may expose their athlete to SG by beginning at the easiest difficulty level (highest frequency of fluctuation between transparent and opaque states). As their athlete improves performance behaviorally, clinicians may increase SG difficulty to increase the visual-cognitive demand.

In addition to the provided Error Scoring System (Table 2), clinicians may use the NASA Task Load Index questionnaire or Borg's Rating of Perceived Exertion scale to optimize the SG difficulty level during training.[127–129] These tools allow clinicians to assess an athlete's perceived level of difficulty performing exercises with SG. For example, if clinicians want to simulate "hard/difficult" sports scenarios with SG, but their athlete rates his or her experience as "moderate," clinicians may increase the visual perturbation by raising the SG difficulty level.

Alternatively, clinicians may opt to only incorporate SG into exercises that are below their athlete's current physical capability initially. For example, if an athlete only recently performed a single-leg *hop* successfully, their clinician may choose to perturbate a single-leg *balance* exercise by adding SG. After successful completion of the single-leg balance exercise with SG, the clinician may then choose to advance the athlete's training by incorporating SG into the harder single-leg hop task. This style of initially incorporating perturbations into exercises that are below a patient's current physical capability is common in rehabilitation.

CONCLUSION

A novel approach to ACL rehabilitation that incorporates sensory reweighting therapy may shift neural processing toward proprioception and reduce the dependency on vision for motor control and/or increase visuomotor efficiency. ACL rehabilitation efforts that incorporate visual-perturbation training supplemented by motor learning principles (visual EF and implicit learning) may fill this gap. Future studies are needed to evaluate the therapeutic efficacy of sensory reweighting therapy in ACL rehabilitation.

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