CLINICAL COMMENTARY

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From Control to Chaos: Visual-Cognitive Progression During Recovery From ACL Reconstruction

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Most anterior cruciate ligament (ACL) injuries occur via noncontact mechanisms (>70%)[4] during movements requiring rapid deceleration or change of direction.[17] After ACL rupture, reconstructive surgery (ACL-R) is a common treatment combined with rehabilitation that aims to restore athletes to at least their previous level of function through range of motion, strength, and neuromuscular training.[2,44,69] Nearly 1 in 4 young athletes who return to pivoting and cutting sport participation suffer a second ACL rupture.[75] Given high reinjury rates and the large percentages of young to elite athletes never returning to sport,[39,73] we question the current efficacy of traditional rehabilitation and return-to-sport (RTS) testing criteria.

A missing element in rehabilitation is targeting the compensatory central nervous system (CNS) adaptations.[51] Common metrics of recovery (ie, muscle strength, patient reported outcomes, and neurocognitive function) are associated with altered CNS activation after ACL-R.[8,12,13,36] Specifically, the regions that clinical metrics are associated with are those that are highly engaged in visual-cognitive functions and cross-modal sensory integration (ie, proprioceptive-visual).[8,15,42,61] We believe that, to target CNS function after ACL-R, a structured framework of progressive visual-cognitive challenges designed to augment traditional rehabilitation is needed. This clinical commentary will (1) lay the neurophysiological foundation for visual-cognitive compensation after ACL-R, (2) provide a theoretical rationale for visual-cognitive dual-task interventions, and (3) outline a framework to implement visual-cognitive dual tasks starting in the acute phase of recovery.

BACKGROUND: Anterior cruciate ligament tear is a serious knee injury with implications for central nervous system (CNS) plasticity. To perform simple knee movements, people with a history of anterior cruciate ligament reconstruction (ACL-R) engage cross-modal brain regions, and when challenged with cognitive-motor dual tasks, physical performance deteriorates. Therefore, people with ACL-R may increase visual-cognitive neural processes for motor control.

CLINICAL QUESTION: What components of CNS plasticity should the rehabilitation practitioner target with interventions, and how can practitioners augment rehabilitation exercises to target injury associated plasticity?

KEY RESULTS: This clinical commentary (1) describes the neurophysiological foundation for visual-cognitive compensation after ACL-R, (2) provides a theoretical rationale for implementing visual-cognitive challenges throughout the return-to-sport continuum, and (3) presents a framework for implementing visual-cognitive challenges from the acute phases of rehabilitation. The Visual-Cognitive Control Chaos Continuum (VC-CCC) framework consists of five training difficulties that progress visual-cognitive challenges from high control to high chaos to better represent the demands of sport.

CLINICAL APPLICATION: The VC-CCC framework augments traditional rehabilitation so that each exercise can progress to increase difficulty and promote sensorimotor and visual-cognitive adaptation after ACL-R. *J Orthop Sports Phys Ther 2024;54(7):431-439. Epub 4 June 2024. doi:10.2519/jospt.2024.12443*

KEY WORDS: *anterior cruciate ligament reconstruction, dual task, visual cognition*

CROSS-MODAL NEUROPLASTICITY AND VISUAL-COGNITIVE DUAL-TASK RATIONALE

Neuroplasticity after ACL rupture is likely the result of a partial proprioceptive deafferentation cascade induced by disruption of sensory signals from the knee joint to the CNS in addition to repetitive use of modified motor behaviors.[33,72] Specifically, cross-modal brain regions that play a role in cognitive control of movement and multisensory integration are impacted after ACL-R.[3,28,51] Cross-modal regions

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examine the congruency of temporal and spatial characteristics across senses, facilitating a seamless integration for instance, between vision and touch.[21,38] The extent of cross-modal plasticity can depend in part on the severity of deafferentation.[56] Also, attention can modulate cross-modal plasticity due to the functional and anatomical connectivity between cross-modal and attentional brain regions.[6,22] The cross-modal regions activated during knee movement after ACL-R are also active during tasks that require external focus of attention, working memory, and visual-spatial processing (ie, precuneus, lingual gurus, posterior cingulate cortex).[6,41,45] Our data suggest that cross-modal regions like the lingual gyrus within the medial occipital cortex may increase activity to compensate and preserve knee motor control, especially in cases with less functional recovery such as low quadriceps limb symmetry index.[13] Additionally, when compared to healthy controls, individuals with ACL-R may activate the posterior parietal cortex to a greater extent to preserve function on clinical assessments of proprioception and dynamic stability.[8] We suspect that individuals after ACL-R experience greater activity in cross-modal regions due to a combination of deafferentation and rehabilitation, which promotes attending to sensorimotor control via the frontoparietal network (FPN).[8,15]

The FPN consists of anatomically separate but functionally connected attentional and cross-modal cortical "nodes"[9,10] that play a key role in cognitive control of goal-directed behavior.[10] Theoretically, the functional and structural connectivity within the FPN may facilitate cross-modal plasticity associated with ACL-R, promoting a visual-cognitive neural compensation[20] that preserves physical function. This is exemplified by individuals 6 weeks after ACL-R, being able to perform postural stability to the level of controls via greater FPN connectivity.[42] However, as rehabilitation progresses and after return to sport, when performing more challenging dual-task postural control,[46,48] gait,[63] and dynamic cutting paradigms,[29] individuals with ACL-R experience a performance decline relative to controls. An elegant example of this neural compensation framework was recently discovered by Sherman et al. who found that, during a lower extremity response inhibition task, those with ACL-R have greater cortical inhibition and commit more decision accuracy errors to maintain reaction time, compared to healthy controls.[62] While neuroplasticity may preserve some facets of motor control after ACL-R,[8,42] when challenged with dual-task or response inhibition conditions, motor and/or cognitive errors are increased.[62] The intensive visual-cognition demands of sport only serve to amplify the potential for motor coordination errors secondary to neurological changes associated with ACL-R.

THE FOUNDATION OF VISUAL COGNITION IN SPORT

Because visual cognition is multifaceted,[5] we will focus on the athlete's ability to extract task-relevant (ie, ignore irrelevant) visual cues from external stimuli to inform goal-directed movement decisions. Visual-cognitive processes in sport require components of both divided and selective visual attention. The cortical regions active during divided and selective attention overlap with the FPN, are highly engaged during sport and involve regions associated with neuroplastic changes after ACL-R, providing clinicians an avenue for exercise prescription.[65]

Divided attention is often referred to as "dual-tasking" or the ability to simultaneously provide attention to or switch between two or more stimuli.[52] The Limited Resource Theory (LRT) of divided attention, implies only a single pool of attentional resource that is distributed among competing stimuli.[52,53] Imagine a soccer match scenario: two players are giving verbal instruction to the same player simultaneously; forcing an attentional "division", in turn, degrading the potential to respond to both equally. Although the LRT is predominantly used to describe dual-task interference, the Multiple Resource Theory (MRT) acknowledges that not all competing stimuli require the same neural or attentional resources.[74] In the soccer scenario, the stimuli competing for attention are both verbal–auditory stimuli. Therefore, the neural systems (ie, auditory) competing for attention overlap substantially and will experience high interference. According to the MRT, if the stimuli competing for attention come from different sensory modalities (ie, one auditory and one visual), the dual-task interference is lower and attentional resources are more easily divided.

Selective attention is the ability to select pertinent and/or ignore irrelevant stimuli.[18,49] The biased competition model of selective attention indicates that an athlete's attentional allocation directly influences sensory integration neural activity.[50] This process can occur through either top-down or bottom-up attentional allocation. *Top-down selective attention* is voluntary attention that a person allots to a given task for identifying task-relevant stimuli.[18,35] In a corner-kick scenario, strikers position themselves to find the best opportunity to score a goal. At a given moment, the striker chooses to allocate their attention to predicting the spatial location of the ball, or a player's position within the penalty area. *Bottom-up selective visual attention* is derived from a visual stimulus that a person responds to unconsciously without planning and can be modulated by the stimulus intensity.[18,35] Consider a corner kick scenario where players are jostling for position. As the ball passes through the air, it deflects off a player's head, which catches the peripheral attention of a striker who was previously fighting for position. The striker's attention is immediately drawn to the sudden change in ball speed and direction causing an instantaneous switch in attention[24] that allows for a rapid change in goal-directed motor behavior enabling a shot on the goal.

Understanding the differences between divided and selective attention is

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important for ACL-R rehabilitation because they are distinct neurophysiological processes that occur in parallel.[35,70] After ACL-R, rehabilitation tends to preallocate attention to knee motor control and movement quality (ie, knee over toes, do not collapse your knee inward, etc).[23] Because attention is a key modulator of sensory integration neural activity,[50] interventions must challenge divided and selective attentional processes to mitigate attention to the movement strategy when faced with intensive visual-cognitive distractions in sport.

THE VISUAL-COGNITIVE CONTROL CHAOS CONTINUUM

The control-chaos continuum (CCC)[66] addresses qualitative and quantitative aspects of "load" during on-pitch rehabilitation.[16,58] We propose a *visual-cognitive CCC* (VC-CCC) that extends the control to chaos concept to visual-cognitive dual tasks through a phased progression from high stability to increasing levels of cognitive complexity. The VC-CCC is intended to be implemented *as early as possible in the recovery from ACL-R*. In the following section, we share examples of how practitioners might apply the VC-CCC during the acute to intermediate phases of rehabilitation. We encourage practitioners to extrapolate these concepts to recovery from other types of musculoskeletal injuries and across all stages of the RTS process.

There are recent guides to integrating generalized neurocognitive challenges and sensory perturbations into injury prevention training,[71] late-stage rehabilitation,[25,55] and RTS testing.[7,26] There are also compelling arguments to emphasize motor learning theory, such as focus of attention, throughout recovery.[23] The VC-CCC focuses on the acute phase of recovery, which is typically overlooked regarding dual-task challenges. The VC-CCC ultimately progresses to focus on visual-cognitive interventions, provides structure for implementation and progression, and is informed by neurophysiological data specific to those recovering from injury.

Applying VC-CCC

The goal of the VC-CCC (**FIGURE 1**) is to progress *individual exercises* (**FIGURE 2**) throughout the continuum rather than categorizing the *athlete and all the exercises* into a single phase of progress. To depict a sample progression throughout the VC-CCC phases, a straight leg raise (SLR) and a variety of intermediate phase exercises are used. **TABLE 1** outlines the theories of divided and visual selective attention with associated theoretical neural targets through each phase of the VC-CCC, and **TABLE 2** provides additional intermediate-level exercise examples using both high- and low-technology options for visual-cognitive dual-task challenges.

Throughout the VC-CCC, the visual-cognitive dual tasks progress from simply reducing the ability of cognition to compensate for motor control (Phase 2) to directly informing motor control via the addition of linking visual stimuli to response inhibition and decision making (Phase 3-5).[37,43,54] Additionally, the VC-CCC phases progress from isolated visually displayed dual tasks to those requiring motor and cognitive decision making and response inhibition (ie, visual-cognitive dual tasks) with low technological requirements. In Phases 2-5, visual-cognitive dual tasks should be used to induce moderate exercise complexity so that athletes complete 70% of repetitions successfully without error.[1,40,60] We acknowledge that several mechanisms of motor learning occur through rehabilitation such as instructive, reinforcement, and use-dependent mechanisms.[40] However, as sports commonly associated with ACL injury require intensive sensorimotor prediction, rehabilitation with visual-cognitive dual tasks may induce prediction errors at various intensities to

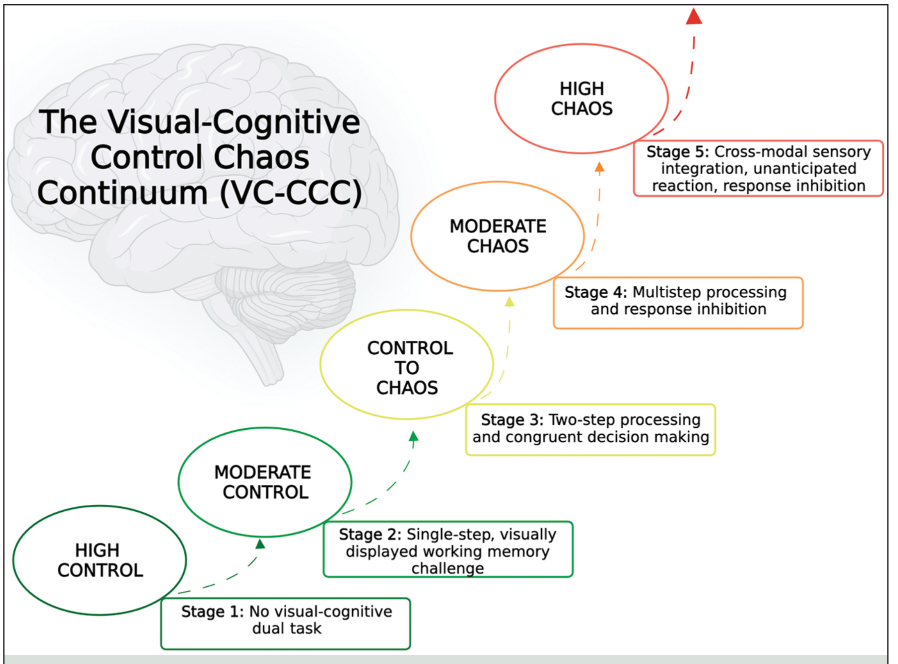

FIGURE 1. Progression of visual-cognitive dual-task interventions from high control to high chaos. Visual-cognitive dual tasks should be progressed strategically through isolated working memory to multi-sensory response inhibition type tasks. This progression targets both divided and selective attention neural mechanisms. The practitioner should monitor both physical and cognitive performance to ensure maximal effort in both domains.

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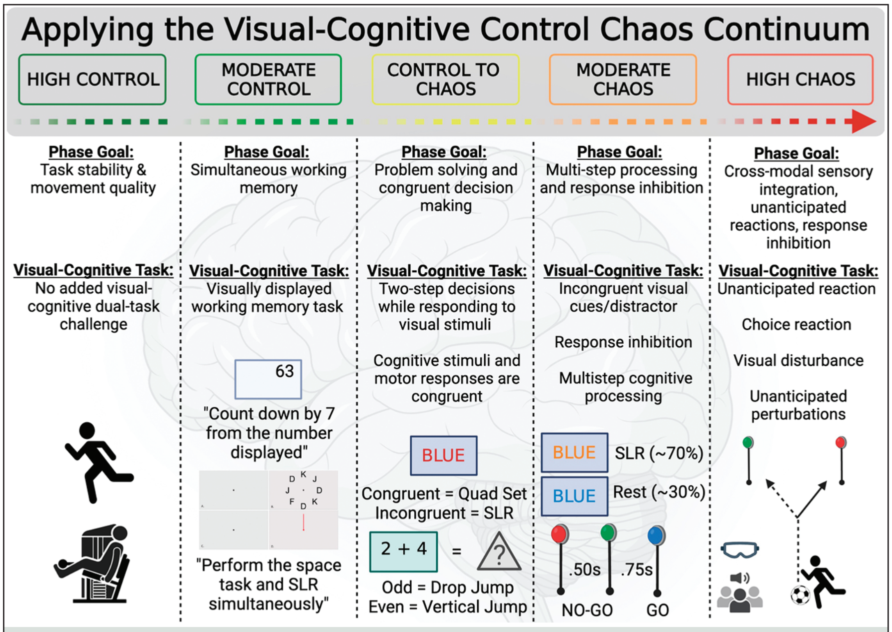

FIGURE 2. Visual Cognitive-Control Chaos Continuum phase goals and VCDT examples for acute to intermediate exercise examples from high control to high chaos with various modes of technology. *High Control* – No added VCDT. *Moderate Control* – Visually displayed working memory task during continuous repetitions. *Control to Chaos* – Visually displayed congruent decision-making task using a pretimed slide deck. *Moderate Chaos* – Visually displayed decision-making tasks with response inhibition. The inhibition trials occur much less frequently than the non-inhibition trials. Variation in timing between stimuli is recommended. Light systems can also be used to display visual cues. *High Chaos* – In virtual reality, a red vs green light is displayed and indicates which leg the athlete responds with in conjunction with congruent auditory stimuli. The athlete may experience unanticipated physical perturbations from the practitioner. Abbreviations: SLR, straight leg raise; VCDT, visual-cognitive dual task.

ultimately promote sensorimotor adaptation. Therefore, practitioners should use technology as available to create phased progressions that ultimately require intensive visual-spatial processing and decision making.

VC-CCC Phase 1: High Control

The focus should be on *task stability and movement quality*. Phase 1: High Control consists of traditional exercise with no added visual-cognitive load, and athletes are cued to complete repetitions at their discretion (**FIGURE 1** and **FIGURE 2**). Progression between VC-CCC phases does not require completely errorless exercise performance (ie, SLR without lag 10/10 repetitions vs 7/10 repetitions). In fact, if performance is errorless, the challenge of the exercise alone may not be difficult enough for learning.[40] Therefore, the time spent within high control may be as short as one session or even a single set of an exercise (**TABLE 1** and **TABLE 2**).

VC-CCC Phase 2: Moderate Control

The goal is to layer a *single-step, visually displayed working memory challenge* on to a continuous exercise (**FIGURE 1**). A continuous visual-cognitive dual task can create a mild cognitive-motor interference through divided attention mechanisms. The rationale for implementing a *visually-mediated divided attention task* is to dissociate cognition from motor control. Instead of allowing an athlete to "think" intently on completing an isometric quadriceps contraction, which may foster a movement strategy dependent on attention for motor control, implementing a Moderate Control intervention requires the athlete to maintain both physical and cognitive performance. Like Phase 1: High Control, this mildly divided attention task may only induce moderate variability in the exercise for a single set of an exercise or one treatment session.

To add single-step working memory to an active SLR, the practitioner may ask the athlete to pace their repetitions to a visual metronome (ie, blinking screen) or to complete simple math displayed on a tablet/computer screen that simultaneously displays while performing the SLR exercise. The same visual-cognitive challenges can be overlaid to several exercises of varying difficulty. For example, as the athlete progresses in rehabilitation and has the physical competency to perform a split squat, the simple arithmetic slides can be administered simultaneously during repetitions. While the athlete is performing the working memory task, the practitioner should be analyzing *both the physical and cognitive performance* to ensure effort in both domains.

VC-CCC Phase 3: Control to Chaos

Phase 3 begins to integrate *problem solving and congruent decision making* with continuous exercises. The visual-cognitive dual tasks should include *two-step processing* where the athlete completes a congruent working memory task (step 1) and then completes a predetermined exercise (step 2). The goal of phase 3 is to transition from visually mediated dual tasks (Phase 2) to visual-cognitive dual tasks that link visual stimulus to a particular motor action. If the technology and environment allow, practitioners should consider adding a spatial element to the visual stimuli presented to stimulate visual search.

For example, a practitioner may instruct an athlete to complete a supine SLR or an isometric quadriceps contraction dependent on the visual-cognitive dual task. The visual-cognitive dual task may be a pretimed slide deck with a Stroop Test (ie, the word BLUE is depicted in the same or different color than the word). Prior to starting the exercise, the athlete and practitioner indicate that congruent images (ie, the word BLUE is in blue font) indicate completion of a 5-second quadriceps

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TABLE 1	Theoretical visual-cognitive targets by VC-CCC phase			
High Control	**Moderate Control**	**Control to Chaos**	**Moderate Chaos**	**High Chaos**
Divided Attention:	**Divided Attention:**	**Divided Attention:**	**Divided Attention:**	**Divided Attention:**
None	Limited Resource Theory Targets the prefrontal cortex and primary visual cortices through visually mediated working memory tasks.	Limited Resource Theory Targets the prefrontal and premotor cortices challenging working memory and congruent decision making.	Multiple Resource Theory Targets the prefrontal and premotor cortices to remember cues and plan action accordingly. Cues may include both visual and auditory stimuli.	Multiple Resource Theory Targets the prefrontal and premotor cortices to remember cues and plan action accordingly. Cues should include both visual and auditory stimuli and link to goal-directed actions (ie, cross-modal integration).
Selective Attention:	**Selective Attention:**	**Selective Attention:**	**Selective Attention:**	**Selective Attention:**
None	None	Top Down Attention is pre-allocated by the visual-cognitive cue (ie, odd answer indicates jump left) and targets more prefrontal and premotor cortices.	Top Down Attention is pre-allocated to the visual-cognitive cue (ie, odd answer indicates jump left). Bottom Up Pre-allocated attention is interfered by response inhibition (No-Go) stimuli that targets pre-supplementary motor and cerebellar-sensorimotor cortices.	Top Down Patients self-select attentional allocation to perform the goal-directed intervention. Bottom Up Pre-allocated attention is interfered on by unanticipated reactions, choice reactions, and sensory disturbance (ie, visual-perturbation glasses). Interventions should also include response inhibition to target premotor, cerebellar, and sensorimotor regions.

Note: This table aims to visually depict the continuum of visual-cognitive dual-task challenges that progress from relatively "simple" visually mediated divided attention tasks (Moderate Control) to tasks that span various modes of selective and divided attention (High Chaos). We theorize the neural targets of each phase based on level of dual-task difficulty grounded in neurophysiological evidence.[37,43,54] In general, as dual-task difficulty increases, higher level multisensory integration centers become engaged in conjunction with cognitive processing regions. Additionally, when sensorimotor prediction errors are introduced, cerebellar-sensorimotor cortices are targeted. Thus, if a practitioner aims to train motor performance with less compensatory neural activation, the dual task should theoretically aim to take away the compensation strategy. Abbreviation: VC-CCC, Visual-Cognitive Control Chaos Continuum.

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isometric contraction and incongruent images (ie, the word BLUE is in red font) indicate performance of three consecutive SLRs. As an intermediate example, athletes might be performing a forward drop jump landing. Using a computer or digital monitor, a pretimed slide deck of simple math is displayed (ie, 2 + 4 = ?). Answers summing to odd numbers indicate that the athlete should perform a forward double leg drop landing and answers summing to even values indicate upon landing the athlete performs a vertical double leg jump.

In these examples, visual attention is pre-allocated and the visual-cognitive dual-task display using pretimed slides provides both a cognitive and movement selection challenge. Practitioners can easily evaluate physical (ie, jumping mechanics) and cognitive performance (ie, math solutions and exercise selection—drop landing vs vertical double leg jump).

VC-CCC Phase 4: Moderate Chaos

Exercises begin to include *multistep processing and response inhibition* (ie, No-Go) challenges. The goal of phase 4 is to advance the visual-cognitive challenges by incorporating incongruent and response inhibition stimuli and other distractors such as visual and/or auditory stimuli from various spatial locations.

An athlete completing SLRs may observe a Stroop paradigm on a computer or tablet screen that consists of both congruent (approximately 30%; same color word/text) and incongruent (approximately 70%; opposite color word/text) trials.[31,32] While performing continuous SLRs, the athlete says the color of the word on the screen. On incongruent trials, the athlete performs continuous SLRs, and on congruent trials, they perform isometric quadriceps contractions. Simultaneously an auditory "bell" stimulus is played with each slide advancement regardless of congruency. If the auditory stimulus is a "crash" instead of a "bell," the athlete is supposed to perform neither the SLR nor isometric exercise. The addition of an auditory stimulus should not replace but rather augment the visual-cognitive dual task if implemented.

To progress the plyometric example from Phase 3, the same slide deck may now include colored backgrounds. Answers summing to odd numbers indicate that the athlete should perform a forward double leg drop jump landing, answers summing to even values indicate upon landing the

TABLE 2 EXAMPLE INTERVENTIONS BY VC-CCC PHASE AND LEVEL OF TECHNOLOGY

High Control	Moderate Control	Control to Chaos	Moderate Chaos	High Chaos
Limited Technology				
Exercise: Lunge to tricolored targets (self-paced). **Visual-Cognitive Task:** None	**Exercise:** Lunge to tricolored targets. **Visual-Cognitive Task:** Pretimed slide deck of randomized *colors* and transition times (1.25-2.0 seconds).	**Exercise:** Double limb vertical jump or dynamic forward lunge. **Visual-Cognitive Task**: Pretimed slide deck of randomized *simple math*. Odd answer indicates jump and even answer indicates lunge.	**Exercise:** Double limb vertical jump or dynamic forward lunge. **Visual-Cognitive Task:** Pretimed slide deck of randomized simple math on slides with *colored backgrounds*. Odd answer indicates jump and even answer indicates lunge. *Orange background indicates NoGo.*	**Exercise:** Four-corner reactive cone tap (submaximal speed). **Visual-Cognitive Task:** Pretimed slide deck with colors (paced at 2.0-2.5 seconds). Touch the cone corresponding to the slide color and return the soccer ball back to the target (visual perturbation glasses may be added).
Greater Technology				
Exercise: Split stance lunge. **Visual-Cognitive Task:** None	**Exercise:** Split stance lunge. **Visual-Cognitive Task:** *Reaction light system – Memorize a sequence of three to eight lights* during the lunge set, then place the lights in appropriate order and recall color after each set. *Object manipulation* – Catch the Y stick color that is called (ie, Catch the "RED" side of the object while you lunge).	**Exercise:** Dynamic lateral lunge. **Visual-Cognitive Task:** *Reaction light system* – Two lights are in front of the person on tripods. *A green light indicates lunge right. A red light indicates lunge left.* Lights appear in randomized order on either tripod. *Virtual reality* – Avoid the obstacles by lunging away from them.	**Exercise:** Dynamic lateral lunge. **Visual-Cognitive Task:** *Reaction light system* – Two lights are in front of the person on tripods. A green light indicates lunge right. A red light indicates lunge left. *A blue light displayed at the same time as Red/Green indicates NoGo.* Lights appear in randomized order on either tripod.	**Exercise:** Submaximal directional ball dribble. **Visual-Cognitive Task:** *Reaction light system* – Practitioner calls out a direction to dribble a soccer ball (ie, forward, backward, etc). 4 to 6 lights are arranged at various depths in front of the athlete. They flash a series of colors to be memorized with spatial location.

Note: The exercise examples above transition into intermediate phases of recovery and use both low technology and high technology examples. The authors acknowledge that practice setting may be a rate limiting factor as to what technology can be used to implement visual-cognitive dual-task challenges. The examples above are meant to represent access to both limited and greater technology. Please see ***SUPPLEMENTAL VIDEOS*** *for limited technology examples.*
Abbreviation: VC-CCC, Visual-Cognitive Control Chaos Continuum.

athlete performs a submaximal double leg jump, if either is presented on a slide with a "red" background, no exercise is performed. Response inhibition should occur on fewer than half of the trials to mitigate habituation to inhibition trials.[31,32] As sports require continuous instances of response inhibition, we suggest using higher proportions of congruent trials. In situations where greater technological resources are available, devices like Stroboscopic glasses, smartphone virtual reality, or reaction light training systems can be integrated. Multistep cognitive processing is vital in sports, especially inhibition of intended movement sequences based on new sensory information. It is paramount that practitioners quantitatively *assess both physical and cognitive performance* and encourage maximal effort in both the physical and cognitive domains.

VC-CCC Phase 5: High Chaos

The goal is to mimic the visual-cognitive demands of sport by employing an intervention that requires an athlete to engage both divided and selected attentional resources while emphasizing *integration of stimuli from multiple senses*. Visual-cognitive interventions should include unanticipated reactions, choice reactions (including go/no go signals), visual disturbance (stroboscopic glasses), and unanticipated physical perturbations (ie, tackle pad contact). Mimicking the visual-cognitive demands of sport does not require that the exercise or visual-cognitive dual task are sport-specific. The expectation is that the athlete can perform the physical exercise under any of the progressive levels of visual-cognitive challenges with both quality motor and visual-cognitive performance (ie, minimal cognitive-motor interference). Therefore, the athlete is skilled enough in both the physical and cognitive domains where the dual-task nature of the exercise with highly chaotic challenges is relatively habitual, as these are the domains under which athletes participate in sport.

To progress the SLR task from Phase 4, unanticipated manual perturbations can be simultaneously applied by the practitioner and/or a teammate while using the same visual-cognitive dual-task challenge. Additionally, in the Phase 4 intermediate example, the athlete may progress to Phase 5 by wearing visual disturbance glasses or catching a multicolor ball/wand during the task. Phase 5 is about creating both physical and cognitive chaos to challenge dual-task interference in a similar neural context as sport. Practitioners should aim to incorporate interventions that require decision making via integrating multiple

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sensations (ie, auditory, visual, somatosensory) to mitigate attentional compensation (ie, FPN). Practitioners should also avoid pretuning an individual's attention to focus on either the cognitive or physical outcome and promote optimizing performance in both domains.

FUTURE RESEARCH

Future research must parse out whole brain neural and neurocognitive contributions to (1) ACL injury and recovery, (2) the impact to the uninvolved limb,[59] and (3) investigate how individuals who chose to undergo nonoperative management of their injury respond. Preliminary work has examined if neural[19,27] and/or neurocognitive[30,47,64] factors play a role in the risk of sustaining an ACL injury. Recent work has also examined the association between neurocognition and noncontact vs contact injury mechanisms.[57] It is unclear if neural or neurocognitive factors precede the injury event, or to what extent the injury, rehabilitation, and daily activity influences neuroplasticity.[14] To date, one fMRI study in an ACL-deficient population found alterations in primary and secondary sensorimotor and posterior inferior temporal gyrus regions.[34] Other seminal work demonstrates that individuals with ACL deficiency have altered neural responses in the primary somatosensory cortex.[11,67,68] However comparing the neurophysiology between individuals who are ACL deficient to those with ACL-R is also insufficient. Longitudinal data are needed to better understand the individual contributions of injury, surgery, and rehabilitation.[14]

KEY MESSAGE FOR PRACTITIONERS

Implementing visual-cognitive challenges in early stages of rehabilitation may reduce the development of compensatory neural strategies that in the long term might be ineffective for RTS participation. Quantifying both visual-cognitive accuracy and physical errors to determine VC-CCC progression is vital to determine if the athlete is engaging in a prioritization strategy (sacrificing performance on cognition to preserve physical performance or vice versa). The goal is to train athletes to optimize both cognitive and motor reserve capacity and mitigate compensating for poor motor capacity with visual-cognitive neural resources.[26]

SUMMARY

Visual-cognitive dual tasks that target the neural mechanisms of divided and selective attention can augment traditional rehabilitation exercises beginning in acute phases. The VC-CCC framework can be used by rehabilitation practitioners as a starting point and was developed through a neurophysiological lens targeted to mitigate visual-cognitive compensation from ACL-R with both low- and high-technology resources. ◉

KEY POINTS

FINDINGS: The Visual-Cognitive Control Chaos Continuum (VC-CCC) is a framework for integrating visual-cognitive challenges through a neurophysiological lens in the rehabilitation continuum beginning in acute phases.

IMPLICATIONS: Augmenting rehabilitation with visual-cognitive dual tasks earlier after anterior cruciate ligament reconstruction may mitigate compensatory reliance on visual-cognitive neural resources.

CAUTION: The VC-CCC should augment standard of care rehabilitation practice after anterior cruciate ligament reconstruction.

STUDY DETAILS

AUTHOR CONTRIBUTIONS: All authors contributed to the manuscript including conception, drafting, revision, and final approval, and are accountable for all aspects of the work.

DATA SHARING: There are no data in this manuscript.

PATIENT AND PUBLIC INVOLVEMENT: No patients were involved in this work and no patient data are reported.

REFERENCES

1. Al-Fawakhiri N, Kayani S, McDougle SD. *Evidence of an optimal error rate for motor skill learning. Published online July 19*, 2023:2023.07.19.549705. https://doi.org/10.1101/2023.07.19.549705
2. Andrade R, Pereira R, van Cingel R, Staal JB, Espregueira-Mendes J. How should clinicians rehabilitate patients after ACL reconstruction? a systematic review of clinical practice guidelines (CPGs) with a focus on quality appraisal (AGREE II). *Br J Sports Med.* 2020;54:512-519. https://doi.org/10.1136/bjsports-2018-100310
3. Baumeister J, Reinecke K, Weiss M. Changed cortical activity after anterior cruciate ligament reconstruction in a joint position paradigm: an EEG study. *Scand J Med Sci Sports.* 2008;18:473-484. https://doi.org/10.1111/j.1600-0838.2007.00702.x
4. Boden BP, Sheehan FT, Torg JS, Hewett TE. Non-contact ACL injuries: mechanisms and risk factors. *J Am Acad Orthop Surg.* 2010;18:520-527. https://doi.org/10.5435/00124635-201009000-00003
5. Cavanagh P. Visual cognition. *Vision Res.* 2011;51:1538-1551. https://doi.org/10.1016/j.visres.2011.01.015
6. Cavanna AE, Trimble MR. The precuneus: a review of its functional anatomy and behavioural correlates. *Brain.* 2006;129:564-583. https://doi.org/10.1093/brain/awl004
7. Chaaban CR, Turner JA, Padua DA. Think outside the box: incorporating secondary cognitive tasks into return to sport testing after ACL reconstruction. *Front Sports Act Living.* 2022;4:1089882. https://doi.org/10.3389/fspor.2022.1089882
8. Chaput M, Onate JA, Simon JE, et al. Visual-cognition associated with knee proprioception, time to stability, and sensory integration neural activity after ACL reconstruction. *J Orthop Res.* Published online February 23. 2021;40:95-104. https://doi.org/10.1002/jor.25014
9. Cocuzza CV, Ito T, Schultz D, Bassett DS, Cole MW. Flexible coordinator and switcher hubs for adaptive task control. *J Neurosci.* 2020;40:6949-6968. https://doi.org/10.1523/JNEUROSCI.2559-19.2020
10. Cooper PS, Wong ASW, Fulham WR, et al. Theta frontoparietal connectivity associated with proactive and reactive cognitive control processes. *NeuroImage.* 2015;108:354-363. https://doi.org/10.1016/j.neuroimage.2014.12.028
11. Courtney C, Rine RM, Kroll P. Central somatosensory changes and altered muscle synergies in subjects with anterior cruciate ligament deficiency. *Gait Posture.* 2005;22:69-74. https://doi.org/10.1016/j.gaitpost.2004.07.002
12. Criss CR, Lepley AS, Onate JA, et al. Neural correlates of self-reported knee function in individuals after anterior cruciate ligament reconstruction. *Sports Health.* Published online

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March 23. 2022;19417381221079339. https://doi.org/10.1177/19417381221079339

13. Criss CR, Lepley AS, Onate JA, et al. Brain activity associated with quadriceps strength deficits after anterior cruciate ligament reconstruction. *Sci Rep.* 2023;13:8043. https://doi.org/10.1038/s41598-023-34260-2
14. Criss CR, Melton MS, Ulloa SA, et al. Rupture, reconstruction, and rehabilitation: a multi-disciplinary review of mechanisms for central nervous system adaptations following anterior cruciate ligament injury. *Knee.* 2021;30:78-89. https://doi.org/10.1016/j.knee.2021.03.009
15. Criss CR, Onate JA, Grooms DR. Neural activity for hip-knee control in those with anterior cruciate ligament reconstruction: a task-based functional connectivity analysis. *Neuroscience Letters.* 2020;730:134985. https://doi.org/10.1016/j.neulet.2020.134985
16. Davids K. Ecological validity in understanding sport performance: some problems of definition. *Quest.* 1988;40:126-136. https://doi.org/10.1080/00336297.1988.10483894
17. Della Villa F, Buckthorpe M, Grassi A, et al. Systematic video analysis of ACL injuries in professional male football (soccer): injury mechanisms, situational patterns and biomechanics study on 134 consecutive cases. *Br J Sports Med.* Published online June 19. 2020;bjsports-2019-101247. https://doi.org/10.1136/bjsports-2019-101247
18. Desimone R, Duncan J. Neural mechanisms of selective visual attention. *Annu Rev Neurosci.* 1995;18:193-222. https://doi.org/10.1146/annurev.ne.18.030195.001205
19. Diekfuss JA, Grooms DR, Yuan W, et al. Does brain functional connectivity contribute to musculoskeletal injury? A preliminary prospective analysis of a neural biomarker of ACL injury risk. *J Sci Med Sport.* 2019;22:169-174. https://doi.org/10.1016/j.jsams.2018.07.004
20. Dixon ML, De La Vega A, Mills C, et al. Heterogeneity within the frontoparietal control network and its relationship to the default and dorsal attention networks. *Proc Natl Acad Sci.* 2018;115:E1598-E1607. https://doi.org/10.1073/pnas.1715766115
21. Driver J, Noesselt T. Multisensory interplay reveals crossmodal influences on 'sensory-specific' brain regions, neural responses, and judgments. *Neuron.* 2008;57:11-23. https://doi.org/10.1016/j.neuron.2007.12.013
22. Gallace A, Spence C. The cognitive and neural correlates of "tactile consciousness": a multisensory perspective. *Conscious Cogn.* 2008;17:370-407. https://doi.org/10.1016/j.concog.2007.01.005
23. Gokeler A, Neuhaus D, Benjaminse A, Grooms DR, Baumeister J. Principles of motor learning to support neuroplasticity after ACL injury: implications for optimizing performance and reducing risk of second ACL injury. *Sports Med.* 2019;49:853-865. https://doi.org/10.1007/s40279-019-01058-0
24. Gokeler A, Tosarelli F, Buckthorpe M, Della Villa F. Neurocognitive errors are common in non-contact ACL injuries in professional male soccer players. *J Athl Train.* Published online May 26. 2023;59:262-269. https://doi.org/10.4085/1062-6050-0209.22
25. Grooms D, Appelbaum G, Onate J. Neuroplasticity following anterior cruciate ligament injury: a framework for visual-motor training approaches in rehabilitation. *J Orthop Sports Phys Ther.* 2015;45:381-393. https://doi.org/10.2519/jospt.2015.5549
26. Grooms DR, Chaput M, Simon JE, Criss CR, Myer GD, Diekfuss JA. Combining neurocognitive and functional tests to improve return to sport decisions following ACL reconstruction. *J Orthop Sports Phys Ther*. Published online May 15. 2023;1-14. https://doi.org/10.2519/jospt.2023.11489
27. Grooms DR, Diekfuss JA, Criss CR, et al. Preliminary brain-behavioral neural correlates of anterior cruciate ligament injury risk landing biomechanics using a novel bilateral leg press neuroimaging paradigm. *PLOS One.* 2022;17:e0272578. https://doi.org/10.1371/journal.pone.0272578
28. Grooms DR, Page SJ, Nichols-Larsen DS, Chaudhari AMW, White SE, Onate JA. Neuroplasticity associated with anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther.* 2017;47:180-189. https://doi.org/10.2519/jospt.2017.7003
29. Heidarnia E, Letafatkar A, Khaleghi-Tazji M, Grooms DR. Comparing the effect of a simulated defender and dual-task on lower limb coordination and variability during a side-cut in basketball players with and without anterior cruciate ligament injury. *J Biomech.* 2022;133:110965. https://doi.org/10.1016/j.jbiomech.2022.110965
30. Herman DC, Barth JT. Drop-jump landing varies with baseline neurocognition: implications for anterior cruciate ligament injury risk and prevention. *Am J Sports Med.* 2016;44:2347-2353. https://doi.org/10.1177/0363546516657338
31. Hood AVB, Hutchison KA. Providing goal reminders eliminates the relationship between working memory capacity and Stroop errors. *Atten Percept Psychophys.* 2021;83:85-96. https://doi.org/10.3758/s13414-020-02169-x
32. Kane MJ, Engle RW. Working-memory capacity and the control of attention: the contributions of goal neglect, response competition, and task set to Stroop interference. *J Exp Psychol Gen.* 2003;132:47-70. https://doi.org/10.1037/0096-3445.132.1.47
33. Kapreli E, Athanasopoulos S. The anterior cruciate ligament deficiency as a model of brain plasticity. *Medical Hypotheses.* 2006;67:645-650. https://doi.org/10.1016/j.mehy.2006.01.063
34. Kapreli E, Athanasopoulos S, Gliatis J, et al. Anterior cruciate ligament deficiency causes brain plasticity: a functional MRI study. *Am J Sports Med.* 2009;37:2419-2426. https://doi.org/10.1177/0363546509343201
35. Katsuki F, Constantinidis C. Bottom-up and top-down attention: different processes and overlapping neural systems. *Neuroscientist.* 2014;20:509-521. https://doi.org/10.1177/1073858413514136
36. Kim H, Onate JA, Criss CR, Simon JE, Mischkowski D, Grooms DR. The relationship between drop vertical jump action-observation brain activity and kinesiophobia after anterior cruciate ligament reconstruction: a cross-sectional fMRI study. *Brain Behav.* 2023;13:e2879. https://doi.org/10.1002/brb3.2879
37. Kim NY, Wittenberg E, Nam CS. Behavioral and neural correlates of executive function: interplay between inhibition and updating processes. *Front Neurosci.* 2017;11:378. Accessed February 14, 2024. https://doi.org/10.3389/fnins.2017.00378
38. Lacey S, Sathian K. Crossmodal and multisensory interactions between vision and touch. *Scholarpedia J.* 2015;10:7957. https://doi.org/10.4249/scholarpedia.7957
39. Lai CCH, Ardern CL, Feller JA, Webster KE. Eighty-three per cent of elite athletes return to preinjury sport after anterior cruciate ligament reconstruction: a systematic review with meta-analysis of return to sport rates, graft rupture rates and performance outcomes. *Br J Sports Med.* 2018;52:128-138. https://doi.org/10.1136/bjsports-2016-096836
40. Leech KA, Roemmich RT, Gordon J, Reisman DS, Cherry-Allen KM. Updates in motor learning: implications for physical therapist practice and education. *Phys Ther.* 2022;102:pzab250. https://doi.org/10.1093/ptj/pzab250
41. Leech R, Sharp DJ. The role of the posterior cingulate cortex in cognition and disease. *Brain.* 2014;137:12-32. https://doi.org/10.1093/brain/awt162
42. Lehmann T, Büchel D, Mouton C, Gokeler A, Seil R, Baumeister J. Functional cortical connectivity related to postural control in patients six weeks after anterior cruciate ligament reconstruction. *Front Hum Neurosci.* 2021;15:655116. https://doi.org/10.3389/fnhum.2021.655116
43. Leone C, Feys P, Moumdjian L, D'Amico E, Zappia M, Patti F. Cognitive-motor dual-task interference: a systematic review of neural correlates. *Neurosci Biobehav Rev.* 2017;75:348-360. https://doi.org/10.1016/j.neubiorev.2017.01.010
44. Logerstedt DS, Scalzitti D, Risberg MA, et al. Knee stability and movement coordination impairments: Knee Ligament Sprain Revision 2017: Clinical Practice Guidelines linked to the International Classification of Functioning, Disability and Health From the Orthopaedic Section of the American Physical Therapy Association. *J Orthop Sports Phys Ther.* 2017;47:A1-A47. https://doi.org/10.2519/jospt.2017.0303
45. Macaluso E, Frith CD, Driver J. Modulation of human visual cortex by crossmodal spatial attention. *Science.* 2000;289:1206-1208. https://doi.org/10.1126/science.289.5482.1206
46. Miko SC, Simon JE, Monfort SM, Yom JP, Ulloa S, Grooms DR. Postural stability during visual-based cognitive and motor dual-tasks

after ACLR. *J Sci Med Sport*. Published online July. 2020;S1440244020306915. https://doi.org/10.1016/j.jsams.2020.07.008
47. Monfort SM, Pradarelli JJ, Grooms DR, Hutchison KA, Onate JA, Chaudhari AMW. Visual-spatial memory deficits are related to increased knee valgus angle during a sport-specific side-step cut. *Am J Sports Med.* 2019;47:1488-1495. https://doi.org/10.1177/0363546519834544
48. Monfort SM, Simon JE, Miko SC, Grooms DR. Effects of cognitive- and motor-dual tasks on postural control regularity following anterior cruciate ligament reconstruction. *Gait Posture.* 2022;97:109-114. https://doi.org/10.1016/j.gaitpost.2022.07.246
49. Moore T, Zirnsak M. Neural mechanisms of selective visual attention. *Annu Rev Psychol.* 2017;68:47-72. https://doi.org/10.1146/annurev-psych-122414-033400
50. Moores E, Maxwell JP. The role of prior exposure in the capture of attention by items in working memory. *Vis Cogn.* 2008;16:675-695. https://doi.org/10.1080/13506280701229262
51. Neto T, Sayer T, Theisen D, Mierau A. Functional brain plasticity associated with ACL injury: a scoping review of current evidence. *Neural Plast.* 2019;2019:3480512. https://doi.org/10.1155/2019/3480512
52. Oberauer K. Working memory and attention – a conceptual analysis and review. *J Cogn.* 2019;2:36. https://doi.org/10.5334/joc.58
53. Pashler H. Dissociations and dependencies between speed and accuracy: evidence for a two-component theory of divided attention in simple tasks. *Cogn Psychol.* 1989;21:469-514. https://doi.org/10.1016/0010-0285(89)90016-9
54. Peters S, Eng JJ, Liu-Ambrose T, et al. Brain activity associated with dual-task performance of ankle motor control during cognitive challenge. *Brain Behav.* 2019;9:e01349. https://doi.org/10.1002/brb3.1349
55. Piskin D, Benjaminse A, Dimitrakis P, Gokeler A. Neurocognitive and neurophysiological functions related to ACL injury: a framework for neurocognitive approaches in rehabilitation and return-to-sports tests. *Sports Health.* 2022;14:549-555. https://doi.org/10.1177/19417381211029265
56. Rabinowitch I, Bai J. The foundations of cross-modal plasticity. *Commun Integr Biol.* 2016;9:e1158378. https://doi.org/10.1080/19420889.2016.1158378
57. Reiche E, Collins K, Genoese F, et al. Lower extremity reaction time in individuals with contact versus noncontact anterior cruciate ligament injuries after reconstruction. *J Athl Train.* 2024;59:66-72. https://doi.org/10.4085/1062-6050-0428.22
58. Schmuckler MA. What is ecological validity? A dimensional analysis. *Infancy.* 2001;2:419-436. https://doi.org/10.1207/S15327078IN0204_02
59. Schnittjer AJ, Kim H, Lepley AS, et al. Organization of sensorimotor activity in anterior cruciate ligament reconstructed individuals: an fMRI conjunction analysis. *Front Hum Neurosci.* 2023;17:1263292. Accessed February 20, 2024. https://doi.org/10.3389/fnhum.2023.1263292
60. Seidler RD, Kwak Y, Fling BW, Bernard JA. Neurocognitive mechanisms of error-based motor learning. *Adv Exp Med Biol.* 2013;782:10.1007/978-1-4614-5465-6_3. https://doi.org/10.1007/978-1-4614-5465-6_3
61. Sherman DA, Baumeister J, Stock MS, Murray AM, Bazett-Jones DM, Norte GE. Weaker quadriceps corticomuscular coherence in individuals following ACL reconstruction during force tracing. *Med Sci Sports Exerc.* Published online November 7. 2022;55:625-632. https://doi.org/10.1249/MSS.0000000000003080
62. Sherman DA, Baumeister J, Stock MS, Murray AM, Bazett-Jones DM, Norte GE. Inhibition of motor planning and response selection after anterior cruciate ligament reconstruction. *Med Sci Sports Exerc.* 2023;55:440-449. https://doi.org/10.1249/MSS.0000000000003072
63. Shi H, Ren S, Miao X, et al. The effect of cognitive loading on the lower extremity movement coordination variability in patients with anterior cruciate ligament reconstruction. *Gait Posture.* 2021;84:141-147. https://doi.org/10.1016/j.gaitpost.2020.10.028
64. Swanik CB, Covassin T, Stearne DJ, Schatz P. The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. *Am J Sports Med.* 2007;35:943-948. https://doi.org/10.1177/0363546507299532
65. Szczepanski SM, Pinsk MA, Douglas MM, Kastner S, Saalmann YB. Functional and structural architecture of the human dorsal frontoparietal attention network. *Proc Natl Acad Sci.* 2013;110:15806-15811. https://doi.org/10.1073/pnas.1313903110
66. Taberner M, Allen T, Cohen DD. Progressing rehabilitation after injury: consider the 'control-chaos continuum'. *Br J Sports Med.* 2019;53:1132-1136. https://doi.org/10.1136/bjsports-2018-100157
67. Valeriani M, Restuccia D, Di Lazzaro V, Franceschi F, Fabbriciani C, Tonali P. Central nervous system modifications in patients with lesion of the anterior cruciate ligament of the knee. *Brain.* 1996;119:1751-1762. https://doi.org/10.1093/brain/119.5.1751
68. Valeriani M, Restuccia D, Di Lazzaro V, Franceschi F, Fabbriciani C, Tonali P. Clinical and neurophysiological abnormalities before and after reconstruction of the anterior cruciate ligament of the knee. *Acta Neurol Scand.* 1999;99:303-307. https://doi.org/10.1111/j.1600-0404.1999.tb00680.x
69. van Melick N, van Cingel REH, Brooijmans F, et al. Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus. *Br J Sports Med.* 2016;50:1506-1515. https://doi.org/10.1136/bjsports-2015-095898
70. Vossel S, Geng JJ, Fink GR. Dorsal and ventral attention systems: distinct neural circuits but collaborative roles. *Neuroscientist.* 2014;20:150-159. https://doi.org/10.1177/1073858413494269
71. Walker JM, Brunst CL, Chaput M, Wohl TR, Grooms DR. Integrating neurocognitive challenges into injury prevention training: a clinical commentary. *Phys Ther Sport.* 2021;51:8-16. https://doi.org/10.1016/j.ptsp.2021.05.005
72. Ward S, Pearce AJ, Pietrosimone B, Bennell K, Clark R, Bryant AL. Neuromuscular deficits after peripheral joint injury: a neurophysiological hypothesis. *Muscle Nerve.* 2015;51:327-332. https://doi.org/10.1002/mus.24463
73. Webster KE, Feller JA, Klemm HJ. Second ACL injury rates in younger athletes who were advised to delay return to sport until 12 months after ACL reconstruction. *Orthop J Sports Med.* 2021;9:2325967120985636. https://doi.org/10.1177/2325967120985636
74. Wickens CD. Multiple resources and performance prediction. *Theor Issues Ergon Sci*. 2002;3:159-177. https://doi.org/10.1080/14639220210123806
75. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Am J Sports Med.* 2016;44:1861-1876. https://doi.org/10.1177/0363546515621554

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