Published in final edited form as:

Phys Ther Sport. 2021 September ; 51: 8–16. doi:10.1016/j.ptsp.2021.05.005.

Integrating Neurocognitive Challenges into Injury Prevention Training: A Clinical Commentary

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Abstract

Despite the efforts of many traditional lower extremity injury prevention programs (IPP), the incidence of anterior cruciate ligament injuries in young athletes continues to rise. Current best practices for IPPs include training lower extremity neuromuscular control and movement quality during cutting, jumping, and pivoting. Emerging evidence indicates neurocognition may contribute to injury incidence and injury risk biomechanics. Therefore, IPP outcomes may improve if clinicians also consider neurocognitive contributions to neuromuscular control and athletic performance. A substantial barrier to neurocognitive challenge integration during injury prevention training in the group setting is the lack of a structured neuromuscular and neurocognitive progressions. Therefore, our aim is to provide clinicians with a defined framework and recommendations from clinical experience for how to implement neurocognitive challenges within group IPPs that requires minimal extra time and resources. This clinical commentary proposes a three-phase model adopted from motor learning literature to simultaneously progress neuromuscular and neurocognitive through a structures IPP.

Level of Evidence: 5

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Keywords

injury prevention program; anterior cruciate ligament; neurocognition; motor learning

Introduction

The incidence of musculoskeletal injury in high school athletics, such as anterior cruciate ligament (ACL) injuries, has continued to rise over the past ~20 years.[1] One tool used to reduce injury rates are injury prevention programs (IPP), which aim to decrease injury risk by training neuromuscular control during dynamic movements (e.g., landing, cutting).[2] While IPPs demonstrate suitable effectiveness,[3,4] approximately 33–50% of the variance in injury risk remains unexplained with current programs.[5] Current standard of care IPPs focus on improving isolated movement mechanics, such as landing from a jump, but do not demonstrate robust transfer to the variety of dynamic movement demanded in sport scenarios.[6–9] Thus, it is plausible that incorporating novel elements that contribute to injury risk and facilitate neuromuscular adaptation transfer to sport may also improve overall IPP effectiveness.

The typical risk factors targeted in standard ACL IPPs include reduced knee flexion and increased knee abduction during landing and cutting activities, and hip extensor and external rotator strength.[2,10–12] However, the common non-contact mechanism of ACL injury may not be entirely explained by mechanical factors alone, as neurocognitive deficits also contribute to injury risk.[13,14] In addition to decreased neurocognition directly increasing injury risk, two prospective studies have identified altered sensorimotor brain functional connectivity in high school athletes who later went on to suffer an ACL injury.[15,16] Decreased connectivity between cortical sensory and motor regions may contribute to slower processing speeds and reaction to environmental stimuli during sport participation, further implicating neurocognitive function as an ACL injury risk factor.[15,16] A separate study identified an association between baseline neurocognitive function on computerized assessment (reaction time and visual motor processing speed) and increased knee abduction, ground reaction force and anterior tibial shear force during unanticipated or reactive landing.[17] This growing body of literature warrants consideration of integrating neurocognition into IPPs to improve program efficacy and potentially reduce ACL injury risk by targeting injury-risk variance not explained by IPPs that primarily target mechanical risk factors.

While neurocognitive additions to neuromuscular training have been employed in research trials and in individual rehabilitation,[18,19] a gap in the literature remains for a framework to incorporate neurocognitive elements in the group IPP setting. In the context of this framework and application to sport IPPs, we refer to neurocognitive challenge as any task (mental, visual, auditory, verbal, kinesthetic, etc.) that substantially occupies the athletes' cognitive attention (whether partially or wholly) simultaneously during the execution of a movement task or traditional IPP exercise. To date, there is a substantial gap in the literature pertaining to effective and efficient clinical examples detailing the administration of group injury prevention training with neurocognitive elements. The proposed program herein details how clinicians can integrate neurocognitive training within group IPPs. Since traditional IPPs are administered in a group or team setting rather than one-on-one like in rehabilitation and research, unique challenges (expanded upon in section "Overall Neurocognitive IPP Tips from the Field") arise, indicating a need for clearly defined methods to guide clinical practice on how to feasibly augment group IPPs with neurocognitive training. The proposed program builds on a prior recommendation to incorporate open-skill practice to facilitate neuromuscular adaptation transfer to sport by engaging a progressive neurocognitive approach that has been clinically employed in the group IPP setting.[20,21] This clinical commentary aims to provide a starting framework for the clinician to begin incorporation of neurocognitive challenges, frequency, intensity, duration, and progression that can be overlaid or implemented in parallel with traditional IPP exercises.

Implementation

The ecological demands of sport challenge athletes' neurocognitive processing abilities (e.g., unanticipated reactions, working memory, visuospatial processing.). By training athletes' neuromuscular control under various neurocognitive conditions, clinicians may reduce injury risk and improve motor control adaptation for sport.[22,23] As there is no accepted standard for progressive neurocognitive challenges within neuromuscular training, the suggested framework is based upon the Fitts and Posner phases of motor learning (cognitive, associative, autonomous) to guide clinicians on how to add and progress neurocognitive challenges in a group IPP.[24,25] This combined neurocognitive and neuromuscular IPP framework is grounded in three phases: 1) athletes learn the basic neuromuscular skill with limited neurocognitive challenge (cognitive phase); 2) clinicians increase the neurocognitive challenge as athletes demonstrate more consistent neuromuscular control (associative phase); and 3) as athletes demonstrate automatic neuromuscular control (i.e., fluid and consistent movements) with minimal attentional demands, clinicians increase the neurocognitive complexity (autonomous phase). Throughout these phases, techniques that minimize clinician burden and time to complete the program are emphasized, such as dyad (partner) training and group-level challenges to working memory and decision-making (Table 1).

The proposed standardized progression of neurocognitive challenges in a group IPP provides clinicians a baseline framework to strategically increase neurocognitive challenges and integrates consideration for motor learning and neuromuscular control. For example, if neuromuscular control (i.e., observable extremity control related to injury risk motions of stiffened landings or non-neutral joint alignment) diminishes with the addition/progression of a neurocognitive challenge, the challenge may be too great for the athletes at that time and should be reduced to recover neuromuscular control. Though some level of movement variability should be expected (especially with progressive challenges), a clinician's judgement is vital to determine what qualifies as a *sufficient* decrement in neuromuscular control to warrant reducing the neurocognitive challenge. Therefore, clinicians might delay neuromuscular *progression* (e.g., complexity of movement) of a task until neuromuscular control during performance is acceptable under the neurocognitive challenge. As athletes progress through the phases of motor learning within the IPP, clinicians should increase neurocognitive difficulty to maintain a sufficient neuromuscular challenge. Of note, neurocognitive challenges do not need to be sport-specific as long as they challenge the same *underlying neurocognitive processes* of sport (e.g., working memory, rapid decision making, visuospatial processing). The goal of overlaying neurocognitive challenges with neuromuscular control exercise is to train cognition and motor function in an interactive manner to meet the ecological demands of sport. In other words, cognition in sport is used to integrate environmental stimuli (i.e., player position, sports balls, opponents) and make strategic decisions.[26,27] However, traditional exercises in prevention training are prescribed in a manner that trains athletes to overly think about their movement (i.e., "do not let your knees go over your toes in a squat") or use vision to compensate for stability (i.e., "attend to the motion or joint directly or in a mirror while jump training"). Thus, incorporating neurocognitive challenges (even if not sport-specific) limits athletes from utilizing cognitive processing to compensate for inadequate neuromuscular control of dynamic movements.[28–30]

Phase 1 - Cognitive Phase: Neuromuscular Development Without Neurocognitive Challenge

The primary goal of training in the first (cognitive) phase is for athletes to acquire the basic neuromuscular control necessary to complete the IPP exercises (Table 1). Clinicians should use minimal neurocognitive challenges during this phase to allow athletes to first achieve competent fundamental neuromuscular control before burdening the neurocognitive system. Adding neurocognitive challenges during the cognitive phase may result in excessive neuromuscular errors by pulling attention away from neuromuscular control and stunting the acquisition of "good" neuromuscular control during the IPP exercises. However, during this phase of motor learning, clinicians may opt to use a variety of cuing strategies (e.g., external focus of attention, implicit/analogy-based feedback) to improve neuromuscular control (Table 2).[31–33] When athletes consistently demonstrate appropriate neuromuscular control, clinicians may then add a simple neurocognitive challenge (e.g., dual-task) near the end of the cognitive phase to assess their athletes' readiness to progress to the second phase of training.

Throughout the proposed framework, it is imperative that clinicians monitor neuromuscular control errors when considering whether their athletes are ready for the addition of a neurocognitive challenge. In the following two stages, the proposed IPP framework suggests that clinicians aim to add a neurocognitive challenge that elicits no more than 1 to 2 neuromuscular control errors (moderate level), indicating that the overall task complexity is appropriately challenging to the athlete (Table 3). However, multiple neuromuscular control errors (3+) or single severe errors may indicate that an athlete is not ready for the neurocognitive challenge and may benefit from additional focused training on the fundamental movement parameters of the exercise. As prior work validating qualitative errors against quantitative laboratory 3D motion analyses metrics during dynamic performance have indicated 1–2 errors separating excellent from good to moderate performance and 3 errors separating excellent from poor performance, thus we recommend a similar threshold for progression.[34] Clinicians can use the Landing Error Scoring System

(LESS) to quantify acceptable neuromuscular control, since it provides a checklist of errors to monitor during training in addition to those provided in (Table 3).[29,35] The LESS is a reliable tool to identify impaired neuromuscular control during a drop vertical jump in individuals at risk for ACL injury.[36–38] Reliable objective assessment of single leg squat[39] and single leg hop[40] mechanics using the Qualitative Analysis of Single Leg Loading (QASLS) scoring form is also available, and appropriate to assess baseline neuromuscular control and monitor errors during the program. While a validated and reliable qualitative tool is not available for every movement that can be completed during an IPP, the error framework of the QASLS and LESS provides a clinical means to "grade" many dynamic movements for determination of athlete readiness for cognitive progressions. Therefore, the use of a quantitative scoring system in this application is for clinicians to monitor and track progress of athletes - not for injury prediction.[41]

Tips from the Field – Cognitive Phase

- *Less is More:* Clinicians should provide simple/concise instructions in a group IPP setting. Simple commands not only standardize instruction/feedback across the groups and instructors, but they also minimize IPP time requirements.
- Monitor the athletes' movement as much as possible during this initial phase and with primary clinical attention toward neuromuscular errors. This is most easily accomplished by utilizing a multidisciplinary team of instructors to maintain an appropriate athlete-to-instructor ratio. The lead clinician overseeing the IPP implementation and progression of group performance can be augmented by the use of "sub-instructors" (e.g., sport coaches or strength and conditioning experts). Integrating sub-instructors allows consistent monitoring of group performance and provides coaches education and awareness of neuromuscular movement expectations.
- If possible, stratify athletes with the qualitative LESS or single leg squat or hop assessments to identify athletes at highest risk and those who may require more attention during training. The athletes with the highest risk should be monitored by the instructor with the most experience.
- Consider monitoring whether fatigue is contributing to performance[42,43] and allow for rest breaks during the early phases of the IPP to help ensure adequate attention and morale. Rating of perceived exertion (RPE) can be used to monitor fatigue and level of exertion.
- Focus on neuromuscular control before adding neurocognitive challenges.

Phase 2 - Associative Phase: Advanced Neuromuscular Control Exercises, Partner Feedback, and Initial Neurocognitive Challenges

The primary goal of training in the second (associative) phase is to build upon the fundamental neuromuscular control developed in the first phase by administering neurocognitive challenges. Adding a neurocognitive challenge requires athletes to generate neuromuscular control solutions that minimize movement errors without focusing cognitive attention to the movement alone. Examining neuromuscular control under neurocognitive challenge can give the clinician insight as to whether the athlete is in the associative phase of motor learning. If the athlete can handle the additional challenge with minimal increase in neuromuscular control errors, progression to this phase of training is warranted. However, clinicians should be cautioned to monitor performance in the cognitive dual-task (e.g., counting cognitive errors), as athletes may overly prioritize maintaining neuromuscular control, neglect the neurocognitive task, and thus experience minimal additional cognitive load or progressive adaptation. Should a clinician identify an athlete who is unable to maintain adequate neuromuscular control under the neurocognitive progression, then the clinician should reduce the neurocognitive difficulty. The three main neurocognitive components in the associative phase are congruent cognitive stimuli, dyad training (both observation and simulation), and simple working memory (Table 1).

A congruent cognitive stimulus is one that can be readily followed and does not require multistep cognitive decision-making. For example, an athlete jumping to the left in response to an instructor's verbal call of "left" is a congruent cognitive stimulus. Dyad training can also be helpful at this stage with a peer model (athlete) as a visual example of the neuromuscular exercise, who acts to mirror and provide interactive feedback.[44,45] Dyad training improves neuromuscular control and enhances motivation by introducing competition between teammates.[44,46–52] Clinicians may implement dyad training by pairing athletes into groups of two and allowing them to either simultaneously perform the exercises (mirroring one another) or alternate who performs the exercise and who delivers the cognitive challenge. Attending to their partners' movements creates a visual distraction from their own movements and attending to their partner's cueing induces a neurocognitive challenge mimicking sport. If neuromuscular control remains adequate after implementing congruent dyad training, clinicians may consider advancing the neurocognitive challenges to more complex working memory tasks in partner format (Table 4).

An example of a working memory neurocognitive challenge is performing simple math. For example, clinicians can instruct their athletes to perform a multiplication problem (e.g., multiply the number of fingers held up for the group by the number 7) and call out the correct answer while performing a skill, such as a lateral bound plyometric jump. Or clinicians could delegate their role as "number generators" to the dyad pairs, where athletes would take turns holding up their fingers for their partners. It is important to note that clinicians can scale the neurocognitive challenge of the math problems according to their athletes' ability, such as starting with very simple addition or simply calling out the number of fingers held up by the instructor or dyad partner. Once the athletes can withstand the neurocognitive challenges of this phase of training with minimal deterioration in motor performance (neuromuscular control errors; Table 3), clinicians may consider transitioning to phase 3 of training.

Tips from the Field – Associative Phase

- Directing athletes' visual attention to the instructor or dyad and not their own body movements is imperative for developing implicit neuromuscular control.

- Dyad training reduces dependence on clinician instruction for implementing neurocognitive challenges.
- Begin with congruent neurocognitive challenge (e.g., signaling "left" means jump left) and advance to simple working memory and digit manipulation challenges (e.g., memorize a string of digits or words during the exercises, add or multiply a number cue by a preset integer, etc.).
- A key theme of the neurocognitive challenge is to force visual attention away from the movement and include a reactive component (the athletes are unable to simply repeat the same movement rep to rep or they must respond to a stimulus for each rep)

Phase 3 - Autonomous Phase: Advanced Neurocognitive-Neuromuscular Interactive Challenges

The primary goal of training in the third (autonomous) phase is to progress the physical exercise challenge and maintain neuromuscular control while athletes are subjected to difficult neurocognitive challenges (Table 4). Fitts and Posner describe automaticity as "routine" performance with minimal cognitive attention to complete a skill.[24,25] As athletes achieve physical expertise with complex neuromuscular exercises, clinicians may progress neurocognitive challenges from congruent stimuli and/or working memory tasks to more complex tasks (e.g., incongruent stimuli, multistep decision-making, anticipation, reactive contexts [Table 1]). Further, the complexity of the neurocognitive challenge should begin to resemble the chaotic sport environment, to promote autonomous neuromuscular control.[53]

In contrast to the congruent cognitive stimuli within the associative phase of training, *incongruent* cognitive stimuli require athletes to respond in opposition to the presented stimulus. An example of an incongruent cognitive-motor task is athletes jumping to the right when the instructor points left. To incorporate multistep decision-making, clinicians can utilize simple math problems whose computed answers indicate a specific type of exercise for the athletes. For example, if performing simple arithmetic operations during an exercise (as mentioned previously in the associative phase), the athletes may be instructed to hop RIGHT if the answer is even or hop LEFT if the answer is odd (for alternative neurocognitive challenges refer to Table 4). This neurocognitive intervention engages athletes in a three-step process: visual search, working memory, and reactive exercise execution to mimic cognitive processing in sport.

In addition to working memory and decision-making, a key component of sports participation is anticipation and reaction to environmental factors. Reactive tasks can be incorporated with hand signals within the autonomous phase. For example, clinicians can instruct their athletes to first perform a hop as quickly as possible to the side of the hand that is raised. To progress the neurocognitive challenge, the athletes may then be instructed to perform a hop as quickly as possible to the opposite direction of the hand that is raised. To add sport-specific object manipulation, soccer athletes may perform ball dribbling while solving math problems given by large flash cards (difficulty can be scaled down by simply stating the number presented). This example requires a motor skill (ball dribbling), visual search (flash cards), and mathematical problem-solving (working memory). Additionally, the dyad training principles from the associative phase can be used as an "opponent" and force the athlete to make an unpredicted reactive movement as opposed to responding to instructor signals. The ultimate goal of the autonomous phase of training is to have athletes perform multiplanar dynamic movements under high cognitive challenge (anticipation/reactive) with adequate neuromuscular control and minimal instructor feedback.

Tips from the Field – Autonomous Phase

- Clinicians should aim to create a neurocognitively taxing environment to mimic the demands of sport by incorporating multistep cognitive processing and incongruent neurocognitive challenges (e.g., working memory, visual search, unanticipated reaction [Table 1]).
- Focus on utilizing *visual stimuli* to induce challenges to neuromuscular control with rapid neurocognitive decision-making during exercise execution.
- Continuously monitor cognitive and neuromuscular errors (Table 3) to tailor relative dosing of both neuromuscular and neurocognitive challenges.
- Clinicians should aim for IPP exercises to be implemented with game speed movements and neurocognitive processing.
- Monitoring the athletes' rating of perceived challenge to gauge difficulty level can provide a means to further tailor the neurocognitive challenge as neuromuscular errors may no longer occur at this stage.[54]

Overall Neurocognitive IPP Tips from the Field

As IPPs are based on extensive biomechanical and clinical research,[55] this clinical commentary is not meant to replace current practice, but to augment it with neurocognitive challenges. Tables 5 through 7 outline an example neurocognitive IPP that has successfully been incorporated by clinicians in high school community outreach roles. In the following paragraphs we discuss several clinical recommendations for successful group IPP integration with neurocognitive challenges that we have learned from our own implementation experiences through community outreach.

Primary barriers to IPP implementation at the high school level include: coach and player perception that little is gained from participation, perception that lower extremity injuries are not a substantial problem, and IPPs are difficult to incorporate at the high school level.[56,57] This literature supports the notion that "buy-in" to IPP effectiveness is a hinderance to implementation at the high school level. Additionally, IPPs currently fail to simulate the neurocognitive aspects of sports, specifically simultaneous cognitive and motor processing (e.g., object tracking, visual working memory and athletic movement with neuromuscular control). An increased emphasis on sport-like neurocognitive demands, in congruence with IPP exercises, may increase stakeholder buy-in from coaches, athletes, and parents. Therefore, novel IPP frameworks that expand upon previously established neuromuscular training programs may provide a means to improve coach and player perception of importance and better prepare athletes for dynamic sporting environments.[58,59]

A key initial step for efficacious program performance is to establish stakeholder support and setting program expectations.[60–63] Padua et al.[60] established a seven step framework for the successful implementation of IPPs, and establishing administrative support is a key first step.[60,62] Obtaining key stakeholder buy-in is crucial to the success of injury prevention efforts and can be achieved by briefing coaches, parents and leadership on the current evidence supporting IPPs and the potential benefits of program implementation. One strategy to provide this type of information includes coaches workshops. Frank et al.[61] found coaches workshops are an effective means to increase coach buy-in and intent to implement IPPs. A pre-program educational overview of “low injury risk” versus “high injury risk” neuromuscular control will limit ambiguity once the program has begun and will help stakeholders better understand optimal movement strategies and their injury risk-reduction importance. Including an overview of neurocognitive progression and why additional neurocognitive challenges will benefit the athlete on the field will also help stakeholders to better understand and support the implementation of this novel training method. Coach workshops can also establish expectations of IPP compliance and outline how to provide performance feedback to athletes. Providing education and establishing expectations prior to program implementation can improve coach, athlete, and family participation.

To ensure success of any IPP, but especially when incorporating the additional neurocognitive challenges, an appropriate athlete-to-instructor ratio is critical to support group training efficiency, monitor neuromuscular control errors, and provide appropriate feedback. We suggest a ratio of 4–6 athletes per 1 instructor; however, this is not always feasible in a community outreach setting. Incorporating a multidisciplinary group of instructors, including team athletic trainers, sports performance specialists, sport coaches and health sciences students (e.g., athletic training, exercise science, physical therapy, etc.), and pairing an experienced instructor with a more novice one is also helpful.[60] Providing adequate support and training to those on the multidisciplinary implementation team is key to successful IPP delivery. A “train the trainer” session should also be performed to ensure efficacy, quality and consistency in program delivery and implementation.[60,61] The individuals involved in employing the IPP should attend the pre-program overview with athletes, families, and coaches so the entire team understands both the performance and compliance expectations. Additionally, we have found it critical to assign a “lead instructor” for each training session. Supplementary instructors support the lead instructor by analyzing neuromuscular control, providing feedback, and assisting with the implementation of neurocognitive challenges. It is then the lead instructor’s responsibility to progress the IPP session (both neuromuscular and neurocognitive challenges) to meet the general group performance level. Ideally the lead instructor is a clinician with experience in evaluating movement quality and engaging in exercise progression, as the addition of neurocognitive elements is certainly an advanced clinical practice. Of note, this framework is not meant to replace the critical thinking and knowledge of the clinician and every exercise (neurocognitive and neuromuscular) will not be suitable for every athletic level (pediatric to elite) and the clinician should consider these recommendations as a starting point and not a rulebook. However, even if the program can be clinician-lead, the presence of the sport coach during training can improve team accountability, program participation, and transfer of neuromuscular and neurocognitive training strategies to in-season warm-ups and practices. We have often found that once sport coaches understand you are trying to stimulate the neurocognitive challenges of sport that can not only support injury-risk reduction but also performance enhancement, they can be creative allies and help develop novel and sport-specific neurocognitive additions to the IPP.

The final overarching clinical pearl pertains to the necessity of clear and *concise* delivery of instruction and feedback in a group setting. In our experience, simple and specific commands foster more cohesive group learning and progression. Standardized external feedback promotes efficient movement retraining and carries into dyad training by allowing the athlete to provide feedback to their partner in a uniform manner (Table 2).[44] Furthermore, pre-planning locations and physical orientations of athletes relative to instructors allows for synchronous performance of the task prompted by the lead instructor's command. Organized groups allow instructors to collectively assess performance for appropriate timing of neuromuscular and neurocognitive progression. If a sufficient number of instructors are available, stratification of groups based on "low" and "high" performers may improve synchronous group performance, ensure appropriate progression, and accommodate the level of feedback each athlete may need within a training session.[64]

Future Implications

While incorporating neurocognitive challenges into a group IPP may improve injury prevention, its efficacy has yet to be tested in a randomized controlled trial or longitudinal study. However, there are minimal to no additional risks associated with adding neurocognitive challenges within an IPP when supervised and progressed by clinicians who monitor neuromuscular control and ensure injury risk movements are minimized. Of note, athletes may slow down or reduce exercise intensity when initially challenged with a dual-task. At first this is acceptable as the athletes accommodate to the new challenge, but IPP administrators should encourage full effort and monitor for drops in exercise intensity. The proposed program (Tables 5–7) continues to use traditional IPP neuromuscular exercises to maintain the fundamental injury reduction effect,[4,59] but adds neurocognitive challenges to simultaneously train the athletes' control of movement dissociated from cognitive processing to mimic sport participation.

Conclusion

Baseline neurocognitive function is associated with ACL injury risk[13] and poor neuromuscular control of drop jump and cutting biomechanics.[17,65] Therefore, implementing neurocognitive training may serve to enhance group IPP efficacy. Integrating neurocognitive challenges in group IPPs creates minimal burden for clinicians and offers a unique avenue for creativity in neuromuscular training. By using a motor learning framework, clinicians can set goals for exercise progression and objectively monitor their athletes' performance. In traditional IPPs, adherence is perhaps the greatest limiting factor to program effectiveness.[3] In our experience, the addition of neurocognitive challenges in group IPPs has the potential to improve IPP adherence, as both athletes and coaches are amicable to the competitive nature and novelty of this type of training. The three-phase framework proposed in this clinical commentary is meant to serve as foundation for future clinician innovation in the field to discover new and simple avenues to engage neurocognition in neuromuscular training.

References

1. Beck NA, Lawrence JTR, Nordin JD, DeFor TA, Tompkins M. ACL Tears in School-Aged Children and Adolescents Over 20 Years. Pediatrics. 2017;139(3):e20161877. doi:10.1542/peds.2016-1877 [PubMed: 28228501]
2. Sugimoto D, Myer GD, Barber Foss KD, Hewett TE. Specific exercise effects of preventive neuromuscular training intervention on anterior cruciate ligament injury risk reduction in young females: meta-analysis and subgroup analysis. Br J Sports Med. 2015;49(5):282–289. doi:10.1136/bjsports-2014-093461 [PubMed: 25452612]
3. Sugimoto D, Myer GD, Bush HM, Klugman MF, McKeon JMM, Hewett TE. Compliance With Neuromuscular Training and Anterior Cruciate Ligament Injury Risk Reduction in Female Athletes: A Meta-Analysis. J Athl Train. 2012;47(6):714–723. [PubMed: 23182020]
4. Grindstaff TL, Hammill RR, Tuzson AE, Hertel J. Neuromuscular Control Training Programs and Noncontact Anterior Cruciate Ligament Injury Rates in Female Athletes: A Numbers-Needed-to-Treat Analysis. J Athl Train. 2006;41(4):450–456. [PubMed: 17273472]
5. Webster KE, Hewett TE. Meta-analysis of meta-analyses of anterior cruciate ligament injury reduction training programs. J Orthop Res. 2018;36(10):2696–2708. doi:10.1002/jor.24043 [PubMed: 29737024]
6. Dicesare C, Kiefer A, Bonnette S, Myer G. Realistic Soccer-Specific Virtual Environment Exposes High-Risk Lower Extremity Biomechanics. J Sport Rehabil. 2019;29:1–23. doi:10.1123/jsr.2018-0237
7. Kristianslund E, Krosshaug T. Comparison of drop jumps and sport-specific sidestep cutting: implications for anterior cruciate ligament injury risk screening. Am J Sports Med. 2013;41(3):684–688. doi:10.1177/0363546512472043 [PubMed: 23287439]
8. Cowley HR, Ford KR, Myer GD, Kernozek TW, Hewett TE. Differences in neuromuscular strategies between landing and cutting tasks in female basketball and soccer athletes. J Athl Train. 2006;41(1):67–73. [PubMed: 16619097]
9. Jones PA, Herrington LC, Munro AG, Graham-Smith P. Is there a relationship between landing, cutting, and pivoting tasks in terms of the characteristics of dynamic valgus?Am J Sports Med. 2014;42(9):2095–2102. doi:10.1177/0363546514539446 [PubMed: 25005852]
10. Hewett TE, Myer GD, Ford KR, et al.Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes. Am J Sports Med. 2005;33(4):492–501. [PubMed: 15722287]
11. Khayambashi K, Ghoddosi N, Straub RK, Powers CM. Hip Muscle Strength Predicts Noncontact Anterior Cruciate Ligament Injury in Male and Female Athletes: A Prospective Study. Am J Sports Med. 2016;44(2):355–361. doi:10.1177/0363546515616237 [PubMed: 26646514]
12. Leppänen M, Pasanen K, Kujala UM, et al.Stiff Landings Are Associated With Increased ACL Injury Risk in Young Female Basketball and Floorball Players. Am J Sports Med. 2017;45(2):386–393. doi:10.1177/0363546516665810 [PubMed: 27637264]
13. 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(6):943–948. doi:10.1177/0363546507299532 [PubMed: 17369562]
14. Wilkerson GB. Neurocognitive Reaction Time Predicts Lower Extremity Sprains and Strains. Int J Athl Ther Train. 2012;17(6):4–9. doi:10.1123/ijatt.17.6.4
15. 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(2):169–174. doi:10.1016/j.jsams.2018.07.004 [PubMed: 30017465]
16. Diekfuss JA, Grooms DR, Nissen KS, et al.Alterations in knee sensorimotor brain functional connectivity contributes to ACL injury in male high-school football players: a prospective neuroimaging analysis. Braz J Phys Ther. Published online July2019:S1413355518310438. doi:10.1016/j.bjpt.2019.07.004

17. Herman D, Barth J. Drop-Jump Landing Varies With Baseline Neurocognition: Implications fro Anterior Cruciate Ligament Injury Risk and Prevention. Am J Sports Med. 2016;44(9):2347–2353. doi:10.1177/0363546516657338 [PubMed: 27474381]

18. Faltus JREHABILITATION STRATEGIES ADDRESSING NEUROCOGNITIVE AND BALANCE DEFICITS FOLLOWING A CONCUSSION IN A FEMALE SNOWBOARD ATHLETE: A CASE REPORT. Int J Sports Phys Ther. 2014;9(2):232–241. [PubMed: 24790784]

19. Niederer D, Plaumann U, Seitz T, et al.How does a 4-week motor–cognitive training affect choice reaction, dynamic balance and cognitive performance ability? A randomized controlled trial in well-trained, young, healthy participants. SAGE Open Med. 2019;7. doi: 10.1177/2050312119870020

20. Herrington LC, Comfort P. Training for Prevention of ACL Injury: Incorporation of Progressive Landing Skill Challenges Into a Program. Strength Cond J. 2013;35(6):59–65. doi:10.1519/SSC.0000000000000013

21. Allen T, Wilson S, Cohen DD, Taberner M. Drill design using the ‘control-chaos continuum’: Blending science and art during return to sport following knee injury in elite football. Phys Ther Sport. 2021;50: 22–35. doi:10.1016/j.ptsp.2021.02.011 [PubMed: 33862346]

22. Grooms DR, Onate JA. Neuroscience Application to Noncontact Anterior Cruciate Ligament Injury Prevention. Sports Health. 2016;8(2):149–152. doi:10.1177/1941738115619164 [PubMed: 26608453]

23. Grooms DR, Kiefer AW, Riley MA, et al.Brain-Behavior Mechanisms for the Transfer of Neuromuscular Training Adaptions to Simulated Sport: Initial Findings From the Train the Brain Project. J Sport Rehabil. 2018;27(5):1–5. doi:10.1123/jsr.2017-0241

24. Fitts PM, Posner MI. Human Performance. Brooks/Cole Pub. Co.; 1967.

25. Fitts PM. Perceptual-motor skill learning. Categ Hum Learn. 1964;47:381–391.

26. Santos R, Duarte R, Davids K, Teoldo I. Interpersonal Coordination in Soccer: Interpreting Literature to Enhance the Representativeness of Task Design, From Dyads to Teams. Front Psychol. 2018;9:2550. doi:10.3389/fpsyg.2018.02550 [PubMed: 30618971]

27. Brooks JX, Cullen KE. Predictive Sensing: The Role of Motor Signals in Sensory Processing. Biol Psychiatry Cogn Neurosci Neuroimaging. 2019;4(9):842–850. doi:10.1016/j.bpsc.2019.06.003 [PubMed: 31401034]

28. Schnittjer A, Simon JE, Yom J, Grooms DR. The Effects of a Cognitive Dual Task on Jump-landing Movement Quality. Int J Sports Med. Published online July 21, 2020. doi:10.1055/a-1195-2700

29. Dai B, Cook RF, Meyer EA, et al.The effect of a secondary cognitive task on landing mechanics and jump performance. Sports Biomech. 2018;17(2):192–205. doi:10.1080/14763141.2016.1265579 [PubMed: 28632053]

30. Kajiwara M, Kanamori A, Kadone H, et al.Knee biomechanics changes under dual task during single-leg drop landing. J Exp Orthop. 2019;6. doi:10.1186/s40634-019-0170-z [PubMed: 30729340]

31. 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. Published online February 5, 2019. doi:10.1007/s40279-019-01058-0

32. Gokeler A, Seil R, Kerkhoffs G, Verhagen E. A novel approach to enhance ACL injury prevention programs. J Exp Orthop. 2018;5(1). doi:10.1186/s40634-018-0137-5

33. Gokeler A, Benjaminse A, Seil R, Kerkhoffs G, Verhagen E. Using principles of motor learning to enhance ACL injury prevention programs. Sports Orthop Traumatol. Published online January 2018. doi:10.1016/j.orthtr.2017.12.006

34. Padua DA, Marshall SW, Boling MC, Thigpen CA, Garrett WE, Beutler AI. The Landing Error Scoring System (LESS) Is a valid and reliable clinical assessment tool of jumplanding biomechanics: The JUMP-ACL study. Am J Sports Med. 2009;37(10):1996–2002. doi: 10.1177/0363546509343200 [PubMed: 19726623]

35. Biese KM, Pietrosimone LE, Andrejchak M, Lynall RC, Wikstrom EA, Padua DA. Preliminary Investigation on the Effect of Cognition on Jump-Landing Performance

Using a Clinically Relevant Setup. Meas Phys Educ Exerc Sci. 2019;23(1):78–88. doi:10.1080/1091367X.2018.1518875

36. Hanzlikova I, Hebert-Losier K. Is the Landing Error Scoring System Reliable and Valid? A Systematic Review. Sports Health. 2020;12(2):181–188. doi:10.1177/1941738119886593 [PubMed: 31961778]
37. Padua DA, DiStefano LJ, Beutler AI, de la Motte SJ, DiStefano MJ, Marshall SW. The Landing Error Scoring System as a Screening Tool for an Anterior Cruciate Ligament Injury–Prevention Program in Elite-Youth Soccer Athletes. J Athl Train. 2015;50(6):589–595. doi:10.4085/1062-6050-50.1.10 [PubMed: 25811846]
38. Fox AS, Bonacci J, McLean SG, Spittle M, Saunders N. A Systematic Evaluation of Field-Based Screening Methods for the Assessment of Anterior Cruciate Ligament (ACL) Injury Risk. Sports Med. 2016;46(5):715–735. doi:10.1007/s40279-015-0443-3 [PubMed: 26626070]
39. Almangoush A, Herrington L, Jones R. A preliminary reliability study of a qualitative scoring system of limb alignment during single leg squat. Phys Ther Rehabil. 2014;1(1):2. doi:10.7243/2055-2386-1-2
40. Lee H, Munro A. A preliminary investigation to establish the criterion validity of a qualitative scoring system of limb alignment during single leg squat and landing. J Exerc Sports Orthop. 2014;1(3). doi:10.15226/2374-6904/1/3/00113
41. Fox AS, Bonacci J, McLean SG, Saunders N. Efficacy of ACL injury risk screening methods in identifying high-risk landing patterns during a sport-specific task. Scand J Med Sci Sports. 2017;27(5):525–534. doi:10.1111/sms.12715 [PubMed: 27292768]
42. Gokeler A, Eppinga P, Dijkstra PU, et al.Effect of fatigue on landing performance assessed with the landing error scoring system (less) in patients after ACL reconstruction. A pilot study. Int J Sports Phys Ther. 2014;9(3):302–311. [PubMed: 24944848]
43. van Melick N, van Rijn L, Nijhuis-van der Sanden MWG, Hoogeboom TJ, van Cingel REH. Fatigue affects quality of movement more in ACL-reconstructed soccer players than in healthy soccer players. Knee Surg Sports Traumatol Arthrosc Off J ESSKA. 2019;27(2):549–555. doi:10.1007/s00167-018-5149-2
44. Benjaminse A, Gokeler A, Dowling AV, et al.Optimization of the Anterior Cruciate Ligament Injury Prevention Paradigm: Novel Feedback Techniques to Enhance Motor Learning and Reduce Injury Risk. J Orthop Sports Phys Ther. 2015;45(3):170–182. doi:10.2519/jospt.2015.4986 [PubMed: 25627151]
45. Shea CH, Wulf G, Whitacre C. Enhancing training efficiency and effectiveness through the use of dyad training. J Mot Behav Wash. 1999;31(2):119.
46. Granados C, Wulf G. Enhancing Motor Learning Through Dyad Practice: Contributions of Observation and Dialogue. Res Q Exerc Sport Wash. 2007;78(3):197–203. doi:10.1080/02701367.2007.10599417
47. McNevin NH, Wulf G, Carlson C. Effects of Attentional Focus, Self-Control, and Dyad Training on Motor Learning: Implications for Physical Rehabilitation. Phys Ther. 2000;80(4):373–385. doi:10.1093/ptj/80.4.373 [PubMed: 10758522]
48. Shebilskem WL, Regian JW, Arthur W, Jordan JA. A Dyadic Protocol for Training Complex Skills. Hum Factors. 1992;34(3):369–374. doi:10.1177/001872089203400309
49. Shea CH, Wright DL, Wulf G, Whitacre C. Physical and observational practice afford unique learning opportunities. J Mot Behav Wash. 2000;32(1):27–36.
50. Shea CH, Wulf G, Whitacre C. Enhancing training efficiency and effectiveness through the use of dyad training. J Mot Behav Wash. 1999;31(2):119.
51. Weinberg RGoal setting and performance in sport and exercise settings: a synthesis and critique. Med Sci Sports Exerc. 1994;26(4):469–477. [PubMed: 8201904]
52. Weinberg RS. Goal setting in sport and exercise: research and practical applications. Rev Educ Fisica UEM. 2013;24(2):171–179. doi:10.4025/reveducfis.v24.2.17524
53. Taberner M, Allen T, Cohen DD. Progressing rehabilitation after injury: consider the ‘control-chaos continuum.’Br J Sports Med. Published online February 8, 2019:bjsports-2018–100157. doi:10.1136/bjsports-2018-100157

54. Hendricks S, Till K, Oliver JL, et al.Rating of perceived challenge as a measure of internal load for technical skill performance. Br J Sports Med. 2019;53(10):611–613. doi:10.1136/bjsports-2018-099871 [PubMed: 30448780]

55. Di Stasi S, Myer GD, Hewett TE. Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. J Orthop Sports Phys Ther. 2013;43(11):777–792, A1–11. doi:10.2519/jospt.2013.4693 [PubMed: 24175599]

56. Norcross MF, Johnson ST, Bovbjerg VE, Koester MC, Hoffman MA. Factors influencing high school coaches' adoption of injury prevention programs. J Sci Med Sport. 2016;19(4):299–304. doi:10.1016/j.jsams.2015.03.009 [PubMed: 25866072]

57. Martinez JC, Mazerolle SM, Denegar CR, et al.Female adolescent athletes' attitudes and perspectives on injury prevention programs. J Sci Med Sport. 2017;20(2):146–151. doi:10.1016/j.jsams.2016.06.009 [PubMed: 27544657]

58. Arundale AJH, Bizzini M, Giordano A, et al.Exercise-Based Knee and Anterior Cruciate Ligament Injury Prevention. J Orthop Sports Phys Ther. 2018;48(9):A1–A42. doi:10.2519/jospt.2018.0303

59. Sadigursky D, Braid JA, De Lira DNL, Machado BAB, Carneiro RJF, Colavolpe PO. The FIFA 11+ injury prevention program for soccer players: a systematic review. BMC Sports Sci Med Rehabil. 2017;9:18. doi:10.1186/s13102-017-0083-z [PubMed: 29209504]

60. Padua DA, Frank B, Donaldson A, et al.Seven steps for developing and implementing a preventive training program: lessons learned from JUMP-ACL and beyond. Clin Sports Med. 2014;33(4):615–632. doi:10.1016/j.csm.2014.06.012 [PubMed: 25280612]

61. Frank BS, Register-Mihalik J, Padua DA. High levels of coach intent to integrate a ACL injury prevention program into training does not translate to effective implementation. J Sci Med Sport. 2015;18(4):400–406. doi:10.1016/j.jsams.2014.06.008 [PubMed: 25086795]

62. Distefano L, Root H, Frank B, Padua D. Implementation Strategies for ACL Injury Prevention Programs: Causes, Impacts, and Conditioning Programs. In: ACL Injuries in the Female Athlete: Causes, Impacts, and Conditioning Programs.; 2018:625–639. doi:10.1007/978-3-662-56558-2_27

63. Short S, Tuttle M. THE GAP BETWEEN RESEARCH AND CLINICAL PRACTICE FOR INJURY PREVENTION IN ELITE SPORT: A CLINICAL COMMENTARY. Int J Sports Phys Ther. 2020;15(6):1229–1234. doi:10.26603/ijspt20201229 [PubMed: 33344038]

64. Fox AS, Bonacci J, McLean SG, Saunders N. Exploring individual adaptations to an anterior cruciate ligament injury prevention programme. The Knee. 2018;25(1):83–98. doi:10.1016/j.knee.2017.11.011 [PubMed: 29329889]

65. 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 Sidestep Cut. Am J Sports Med. 2019;47(6):1488–1495. doi: 10.1177/0363546519834544 [PubMed: 30986095]

66. Gokeler A, Benjaminse A, Hewett TE, et al.Feedback Techniques to Target Functional Deficits Following Anterior Cruciate Ligament Reconstruction: Implications for Motor Control and Reduction of Second Injury Risk. Sports Med. 2013;43(11):1065–1074. doi:10.1007/s40279-013-0095-0 [PubMed: 24062274]

67. Myer GD, Stroube BW, DiCesare CA, et al.Augmented feedback supports skill transfer and reduces high-risk injury landing mechanics: a double-blind, randomized controlled laboratory study. Am J Sports Med. 2013;41(3):669–677. doi:10.1177/0363546512472977 [PubMed: 23371471]

68. Padua DA, DiStefano LJ, Marshall SW, Beutler AI, de la Motte SJ, DiStefano MJ. Retention of movement pattern changes after a lower extremity injury prevention program is affected by program duration. Am J Sports Med. 2012;40(2):300–306. doi: 10.1177/0363546511425474 [PubMed: 22064608]

69. Begalle RL, Distefano LJ, Blackburn T, Padua DA. Quadriceps and hamstrings coactivation during common therapeutic exercises. J Athl Train. 2012;47(4):396–405. doi:10.4085/1062-6050-47.4.01 [PubMed: 22889655]

70. Ekstrom RA, Donatelli RA, Carp KC. Electromyographic analysis of core trunk, hip, and thigh muscles during 9 rehabilitation exercises. J Orthop Sports Phys Ther. 2007;37(12):754–762. doi:10.2519/jospt.2007.2471 [PubMed: 18560185]

71. Konrad P, Schmitz K, Denner A. Neuromuscular Evaluation of Trunk-Training Exercises. J Athl Train. 2001;36(2):109–118. [PubMed: 12937449]

72. Lewek M, Rudolph K, Axe M, Snyder-Mackler L. The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. Clin Biomech Bristol Avon. 2002; 17(1):56–63. doi:10.1016/s0268-0033(01)00097-3

73. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. Am J Sports Med. 2007;35(3):368–373. doi:10.1177/0363546506297909 [PubMed: 17267766]

1. Neurocognition can readily augment traditional injury prevention training to enhance transferability of neuromuscular adaptations to sport.
2. A three-phase model is proposed paralleling the phases of motor learning with neurocognitive loading: cognitive (minimal to no additional neurocognitive challenge), associative (single-step and congruent reactive or working memory stimuli added to neuromuscular exercises) and autonomous (multi-step and incongruent reactive or working memory stimuli).
3. The framework provides a starting point for integration of neurocognition into classic injury prevention exercise, though clinical trials are required to validate efficacy, there is minimal additional time or risk to the athlete to add neurocognitive challenges.
4. Anecdotally the inclusion of neurocognitive challenges increases compliance and program creativity while facilitating neuromuscular control progression.

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Table 1:

Outlined neurocognitive challenges associated with each phase of Fitts and Posner's Phases of Motor Learning.

Training Phase of IPP	Key Training Phase Elements of Neurocognitive Challenge
Cognitive Phase	No neurocognitive challenge Focus on neuromuscular control
Associative Phase	Congruent neurocognitive challenges Dyad Training- mirror movements Dyad Training- partner provides neurocognitive challenge\cue Simple working memory
Autonomous Phase	Incongruent neurocognitive challenges Multistep decision-making Fast anticipation/reactive challenges

Table 2:

Comparison of Verbal Instructions with Internal Body Focus and External Visual Focus (Additional examples can be found in references.[31,44,66]).

Type of Exercise	Instruction with Internal *Body* Focus	Instruction with External *Visual* Focus
Single-leg stance on unstable platform	Keep your balance by stabilizing your body	Keep the bar horizontal
Single-leg squat	Stand on 1 leg and bend your knee while keeping your knee over your foot	Stand on 1 leg and reach your knee toward the cone
Single-leg hop for distance	Jump as far as you can. While jumping, focus on extending your knees as rapidly as possible	Jump as far as you can. While jumping, focus on jumping as close to the cone as possible
Walking lunges	Lunge at an even pace. Bend your hips and knees until your leading knee is flexed to 90. Keep your front knee on top of your foot and prevent buckling inward with knee	Lunge at an even pace. While pretending you have a plank on your back, keep your knee alignment with an imaginary line or if available real straight line on the floor.
Double-leg squat	Bend your knees while keeping your knees over your feet	While bending your knees, reach toward the cones with your hands and point your knees toward the cones.
Double-leg drop jump	Jump down from the box, land with your feet at shoulder width, and bend your knees while keeping knees over toes	Jump down from the box and land with your feet and knee just outside of the markers on the floor.
Vertical jump	Jump as high as you can while concentrating on the tips of your fingers, reaching as high as possible during the jumps	Jump and reach as high as you can while concentrating on the ball.

Table 3:

Neuromuscular control errors for neurocognitive challenge progression.

Level of Neuromuscular Difficulty	Neuromuscular Control Error Range
Low	0 or 1
Moderate	1 to 2
High	3 or more
Neuromuscular Control Errors	**Cognitive Errors**
Stiff landing strategy (decreased knee flexion at landing)	Responding incorrectly to auditory or visual cue
Exaggerated valgus collapse (knee abduction)	Incorrect math problem answer
Contralateral hip drop during landing and/or cutting	Unable to shadow dyad partner
Loss of balance or contralateral foot tap for single leg stability tasks	Delayed reaction time/processing speed (overly slow)

Table 4.

Neurocognitive challenge examples.

Cognitive Challenge	Numeric Example	Alternative Example	Alternate Example
Interference	Instructor flashes odd # signal, but speaks an even # - before training athletes are told which to attend to for exercise selection or movement direction execution	Instructor flashes colored cards but speaks a different color than presented. Before training athletes are told which to attend to for the exercise selection or movement direction (Ex: deck of red and green flashcards, with red (right) and green (left), but instructor says random non-signal colors; Potential progression to: red (lunge) and green (squat) from instructor verbal cue and watch as flash cards cycle and when verbal cue and visual cue match execute a jump)	The instructor utilizes a deck of playing cards, and the athlete is to perform a specific task per suite or per color. (Ex: with hearts perform single leg squat (right), diamonds perform single leg squat (left), spades perform double leg squat, clubs perform double leg jump. Hand Signal: The instructor can point in various directions and the athlete responds with hopping in that direction. Potential progression to: whatever direction the instructor points, the athlete must hop in the opposite direction. Ex: the instructor points left; the athlete must hop right.
Dual task (cognitive-motor)	Counting\adding\multiplying	Memorizing color string of flash cards that cycle with exercise execution	Hand movements with verbal cuing: Example-the instructor will hold their hands up and the athletes are instructed to jump one direction if the right-hand drops, jump the opposite direction if the left hand drops. This could also progress to include a task based on the instructor calling out or holding up an even/odd number. (i.e R hand drop→ jump right; L hand drop→ jump left; even number→ jump forward; odd number→ jump backwards)
Dual task (motor-motor)	Lower extremity plyometrics while either: 1) holding sport instrument\ball, or 2) engaged in upper extremity task simultaneously		
Working memory	Digit span	Word span	Task progression: Athlete must build on a series of tasks, or perform a series of tasks based on instruction. Example: provide instruction on a number of tasks in a row and the athlete must perform in this order (Ex: instruct the athlete in this sequence: squat, squat, hop left, jump back, squat, hop right; the athlete must complete that sequence in order)
Anticipation & Response inhibition	Go - No Go	Sudden signals to stop mid set or rep of exercise	
Spatial tracking	Ball\person\object		Ball toss or sport-specific ball movement. Example: single leg hop R with L foot volley for soccer player; Single leg hop with chest pass for basketball player

Table 5:

Session Considerations/Framework.

A) 3–4 plyometric tasks should be performed each training session. Address various planes of movement within each session B) Start with athletes standing in 2–4 lines, facing the lead instructor C) Sessions should include individual performance, dyad/partner training and a cognitive challenge (based on phases of learning)	
Individual Performance	Initially, the skill is taught/demonstrated and the athlete performs the task individually on the instructors command (ex: the instructor calls out "hop" and the athlete responds by performing the task). Movement correctives provided by instructor, starting with intrinsic feedback and then quickly transitioning to extrinsic feedback modeling
Dyad/Partner Training	The athlete partners with the person in line behind them. Start by alternating roles between lead and follower. The lead initiates movements and the follower mirrors (congruent dyad training). Progress dyad to have the lead athlete provide the neurocognitive stimuli to their follower and rotate throughout the session.
Cognitive Challenge	As skill acquisition of the motor task is accomplished, introduce a progressive cognitive challenge. Starting with simple single step (1 cognitive process) and congruent processing (move as commanded), advancing to multi step (2 processed, or addition of memory) and finally incongruent (move opposite as commanded) or opposing cognitive stimuli relative to neuromuscular execution.

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Table 6:

Example Physical Warm-up Interventions (No Neurocognitive Challenge).[67–73]

Category	Specific Exercises
Posterior Chain Static	Glute Bridges Nordic Hamstring Curls Single Leg Romanian Deadlift
Core Stability Static	Bird Dog Plank (Front and/or Side) Bear Plank
Primitive Dynamic Movements	Bear Crawl Forward/Backward Crab Walks Elephant Walks Inchworm Spiderman

Table 7:

Example Associative Phase Group Injury Prevention Program with Progressive Neurocognitive Challenges.[55]

Session	Plane of Movement	Task	Repetitions/Challenge
1	Sagittal	Step-Hold *Starting in a single leg athletic stance, the athlete takes a step forward and descends quickly into a deep hold position on the contralateral limb. The athlete sustains balance in the landing position for a minimum of 3 seconds.*	2×6 with instructor cueing 2×5 dyad with partner
	Frontal	Double Leg Lateral Jump-Hold *Starting in a double leg athletic stance, the athlete jumps laterally while landing with their knees slightly flexed using a toe to mid-foot landing. The athlete should be instructed to maintain this landing position for a minimum of 3 seconds.*	2×6 with instructor cueing 2×5 dyad with partner
	Transverse	Double Leg 90° Jumps *Starting in a double leg athletic stance, the athlete jumps into the air while rotating 90° during flight, landing in a slightly flexed position using a toe to mid-foot landing. The athlete should be instructed to maintain this double leg landing position for a minimum of 3 seconds.*	2×6 with instructor cueing 2×5 dyad with partner
2	Sagittal	Step-Hold *(see session 1 description)*	1×6 with instructor cueing 2×5 dyad with partner 2×5 neurocognitive task
	Frontal	Double Leg Lateral Jump-Hold *(see session 1 description)*	1×6 with instructor cueing 2×5 dyad with partner 2×5 neurocognitive task
	Transverse	Double Leg 90° Jumps *(see session 1 description)*	1×6 with instructor cueing 2×5 dyad with partner 2×5 neurocognitive task
3	Sagittal	Hop-Hold *Starting in a single leg athletic stance, the athlete hops forward, landing and maintaining balance on the same single leg in a deep hold position. The landing should be maintained for a minimum of 3 seconds. The athlete should hop and land on the same leg.*	2×4 with instructor cueing, in line 2×4 dyad with partner 1×5 neurocognitive task
	Frontal	Single Leg Lateral Hop-Hold (Isolated) *Starting on a single leg athletic stance, the athlete hops laterally while landing with their knee slightly flexed using a toe to mid-foot landing. The athlete should be instructed to maintain this landing position for a minimum of 3 seconds.*	2×4 with instructor cueing, in line 2×4 dyad with partner 1×5 neurocognitive task
	Transverse	Double Leg 180° Jumps *Starting in a double leg athletic stance, the athlete jumps into the air while rotating 180° during flight, landing in a double leg stance with slightly flexed position using a toe to mid-foot landing. The athlete should be instructed to maintain this landing position for a minimum of 3 seconds.*	2×4 with instructor cueing, in line 2×4 dyad with partner 1×5 neurocognitive task
4	Sagittal	Hop-Hold *(see session 3 description)*	1×4 with instructor cueing, in line 1×8 dyad with partner 2×5 neurocognitive task
	Frontal	Single Leg Lateral Hop-Hold (Isolated) *(see session 3 description)*	1×4 with instructor cueing, in line 1×8 dyad with partner 2×5 neurocognitive task
	Transverse	Double Leg 180° Jumps *(see session 3 description)*	1×4 with instructor cueing, in line 1×8 dyad with partner 2×5 neurocognitive task
5	Sagittal	Hop-Hop-Hold *Starting in a single leg athletic stance, the athlete hops forward twice quickly, landing and maintaining balance on one leg in a deep hold position. The landing should be maintained for a minimum of 3 seconds. The athlete should hop and landing on the same leg.*	2×4 with instructor cueing, in line 1×4 dyad with partner 1×4 neurocognitive task

Session	Plane of Movement	Task	Repetitions/Challenge
	Frontal	Single Leg Lateral Hop-Hold (Repetitive) *Starting in a single leg athletic stance, the athlete jumps laterally while landing with their knee slightly flexed using a toe to mid-foot landing. Upon landing, the athlete jumps medially back to the starting position with the same leg. The athlete repeats for a designated amount of time or repetitions.*	2×4 with instructor cueing, in line 1×4 dyad with partner 1×4 neurocognitive task
	Transverse	Single Leg 90° Hops (Turning Laterally) *Starting in a single leg athletic stance, the athlete hops into the air while rotating 90° laterally during flight, landing in a slightly flexed position using a toe to mid-foot landing. The athlete should be instructed to maintain this landing position for a minimum of 3 seconds. If starting on right leg, turn to the right. If starting on the left leg, turn to the left.*	2×4 with instructor cueing, in line 1×4 dyad with partner 1×4 neurocognitive task
6	Sagittal	Hop-Hop-Hold *(see session 5 description)*	1×4 with instructor cueing, in line 2×6 dyad with partner 2×6 neurocognitive task
	Frontal	Single Leg Lateral Hop-Hold (Repetitive) *(see session 5 description)*	1×4 with instructor cueing, in line 2×6 dyad with partner 2×6 neurocognitive task
	Transverse	Single Leg 90° Hops (Turning Laterally) *(see session 5 description)*	1×4 with instructor cueing, in line 2×6 dyad with partner 2×6 neurocognitive task
7	Sagittal	Crossover Hop *Starting in a single leg athletic stance, the athlete hops forward 3 times while crossing over a line each time (if the athlete is performing on the Right leg, they should start on the left side of the line. Hop include: cross over, cross back, cross over). The final landing should be maintained in a deep hold for a minimum of 3 seconds. The athlete should hop and land on the same leg.*	2×4 with instructor cueing, in line 1×4 dyad with partner 1×4 neurocognitive task
	Frontal	Single Leg Lateral Hop-Hop-Hold *Starting in a single leg athletic stance, the athlete hops laterally twice quickly while landing with their knee slightly flexed using a toe to mid-foot landing. Upon landing, the athlete hops back (medially) to the starting position. The athlete repeats for a designated amount of time or repetitions.*	2×4 with instructor cueing, in line 1×4 dyad with partner 1×4 neurocognitive task
	Transverse	Single Leg 90° Hops (Turning Medially) *Starting in a single leg athletic stance, the athlete hops into the air while rotating 90° medial during flight, landing in a slightly flexed position using a toe to mid-foot landing. The athlete should be instructed to maintain this landing position for a minimum of 3 seconds. If starting on right leg, turn to the left. If starting on the left leg, turn to the right.*	2×4 with instructor cueing, in line 1×4 dyad with partner 1×4 neurocognitive task
8	Sagittal	Crossover Hop *(see session 7 description)*	1×4 with instructor cueing, in line 2×6 dyad with partner 2×6 neurocognitive task
	Frontal	Single Leg Lateral Hop-Hop-Hold *(see session 7 description)*	1×4 with instructor cueing, in line 2×6 dyad with partner 2×6 neurocognitive task
	Transverse	Single Leg 90° Hops (Turning Medially) *(see session 7 description)*	1×4 with instructor cueing, in line 2×6 dyad with partner 2×6 neurocognitive task