Associations Between Cognitive Function and ACL Injury-Related Biomechanics: A Systematic Review

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Context: Does lower baseline cognitive function predispose athletes to ACL injury risk, especially when performing unplanned or dual-task movements?

Objective: To evaluate the association between cognitive function and biomechanics related to ACL injuries during cognitively challenging sports movements.

Data Sources: PubMed (MEDLINE), Web of Science, Scopus, and SciELO databases were searched; additional hand searching was also conducted.

Study Selection: The following inclusion criteria had to be met: participants completed (1) a neurocognitive test, (2) a cognitively challenging sport-related task involving lower limbs, and (3) a biomechanical analysis. The following criteria determined exclusion from the review: studies involving participants with (1) recent or current musculoskeletal injuries; (2) recent or current concussion; (3) ACL surgical reconstruction, reviews of the literature, commentary or opinion articles, and case studies.

Study Design: Systematic review using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis Protocols (PRISMA-P) statement and registered at the International Prospective Register of Systematic Reviews (PROSPERO).

Level of Evidence: Level 3.

Data Extraction: Two of authors independently extracted data and assessed the methodological quality of the articles with the Downs and Black and ROBINS-I checklists, to assess methodological quality and risk of bias, respectively.

Results: Six studies with different methodologies and confounding factors were included in this review. Of these 6 studies, 3 were ranked as high-quality, 3 demonstrated a low risk of bias, 2 a moderate risk, and 1 a severe risk. Five studies found a cognitive-motor relationship, with worse cognitive performance associated with increased injury risk, with 1 study reporting the opposite directionality for 1 variable. One study did not identify any interaction between cognitive function and biomechanical outcomes.

Conclusion: Worse cognitive performance is associated with an increased injury risk profile during cognitively challenging movements.

Keywords: ACL; cognition; dual-task; sports injuries; unplanned movements

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Despite its critical importance, injury risk evaluation poses a challenge to researchers and clinicians. Indeed, there is a lack of screening tests capable of successfully and reliably predicting injuries.[6] A major complication in identifying athletes at risk of sustaining an anterior cruciate ligament (ACL) injury is the multifactorial and complex nature of sports injuries themselves.[9] Inconsistency in sport-related movement evaluation and outcome measures makes consensus risk stratification even more difficult.[6,14] Injuries often occur due to the interaction of several determinants.[36]

Among several intrinsic aspects to consider, neurocognition has gained importance recently because of its critical role in organizing movement patterns while processing a large amount of rapidly changing environmental information.[45,62] Lower-level cognitive functions are responsible for basic stimulus processing,[56] while higher-level executive function domains regulate the decision-making process by integrating these incoming stimuli and making goal-oriented decisions from the information at hand.[2] In the context of sports biomechanics, cognitive performance is defined collectively as an athlete's ability to perform tasks related to the following fundamental domains: visual attention, self-monitoring, agility/fine motor performance, processing speed/reaction time, and dual-tasking.[31] These neuropsychological dimensions are proposed to contribute to a mechanism of noncontact ACL lesions.[5,62,63] Athletes adjust movements in response to rapidly changing external stimuli and secondary task requirements, especially in open-skill sports.[18,67] This cognitive-motor interaction offers a plausible explanation for why injuries typically occur in sports context during cognitively challenging tasks such as distracted/perturbed decelerations, landings, and changes of direction.[19,37,41,43,47,64] Motor planning uncertainty caused by the attentional constraints of an athlete's need to monitor and respond to a rapidly changing sports environment may lead to a decline of neuromuscular control, sensory information processing, coordination, and dynamic stability and result in the athlete adopting an injurious movement pattern.[11,12,26,51]

A few studies have evaluated the extent to which poor baseline cognitive performance is associated with greater ACL injury risk. For example, Swanik et al[63] compared the baseline cognitive performance of 80 intercollegiate athletes who sustained a noncontact ACL injury with those from a noninjured matched control group. The authors found differences between groups in all the tested cognitive domains, including verbal and visual memory, processing speed, and reaction time, suggesting that athletes with lower cognitive performance could be at disadvantage for safely managing the cognitively challenging environment of competitive sport. Similarly, Wilkerson[66] demonstrated prospectively that slower reaction time scores were associated with lower extremity sprains and strains among collegiate football players. Moreover, a recent systematic review reported a significant association between cognitive challenges and motor performance in injured athletes.[14] However, additional prospective studies are necessary to more clearly understand potential relationships between cognitive function and lower extremity injury risk. In addition, these studies do not address a key gap in knowledge: how individual differences in cognitive function translate to athletes negotiating the cognitive-motor demands of competitive sport.

In the last few years, an initial body of research devoted to the aforementioned gap in knowledge has emerged. These studies have considered a range of low- and high-level cognitive baseline assessments, dual-task demands, and open-skill movements. This variation in the research methods warrants a summary discussion to provide direction for future research into cognitive-motor relationships as they pertain to sports biomechanics. A recent review by Porter et al[54] began to address this issue, showcasing a relationship between neurocognition and lower-extremity biomechanics. Their main takeaway was that cognitive domains have been linked to subject-specific changes in neuromuscular control as a result of sports-related tasks. However, the review excluded studies that examined cognitively challenging tasks (eg, dual-task or unanticipated movements). In addition, Avedesian et al[5] also reviewed the cognitive-motor relationship related to ACL injuries, analyzing the cognitive performance in both injury occurrences and harmful biomechanics studies. They reported that worse performance on measures of cognition was associated with risky lower extremity biomechanical patterns and that cognitive performance was a significant predictor for subsequent injury. However, a focused discussion of the differences in cognitive domains assessed and cognitive challenges used during biomechanical testing for the included studies was not reported.

To summarize, 2 systematic reviews have started to centralize the existing research on cognitive-motor relationships in open-skill movements, highlighting an effect of baseline cognitive function on movement mechanics during sports-specific tasks. However, despite these recent valuable efforts, it is still unclear which motor tasks and specific traits of the cognitive assessments are most salient to elucidate cognitive-motor relationships. These questions highlight an opportunity to provide further clarity into cognitive-motor relationships pertaining to high-risk knee mechanics.

Therefore, this systematic review aimed to evaluate the association between cognitive function and biomechanics related to ACL injuries during cognitively challenging sports movements. We hypothesized that lower cognitive function would be associated with higher-risk lower limb mechanics during cognitively challenging sport movements. The review and critical evaluation of the methodologies will provide a step forward in assessing noncontact ACL injury risk in athletic populations through evidence-based comprehensive methods.

METHODS

The review protocol was registered at the International Prospective Register of Systematic Reviews (PROSPERO) and developed in line with the Preferred Reporting Items for Systematic Review and Meta-analysis Protocols (PRISMA-P).[59]

Electronic database searches were carried out in PubMed (MEDLINE), Web of Science, Scopus, and SciELO with a publication date filter set between January 1, 1990 and June 30, 2021.

Search Strategy

The search strategy incorporated 3 term sets, created following the PICO method and combined with the ‘AND’ Boolean operator or separated by the ‘OR’ Boolean operator. The search was performed separately by 2 reviewers using the following keywords, divided into the 3 sets: (“cognit*” OR “neurocognit*” OR “visual-motor” OR “visual-spatial” OR “attention” OR “dual-task”) AND (“biomechanics” OR “mechanics” OR “kinematic” OR “kinetic” OR “valgus” OR “abduction” OR “flexion”) AND (“lower limb” OR “lower extremity” OR “leg” OR “knee” OR “ankle” OR “hip” OR “ACL” OR “anterior cruciate ligament”).

Study Selection

The studies selection process is displayed in Figure 1. After removing duplicates, the 2 reviewers independently screened all titles for relevance. All articles with titles irrelevant to the research question were removed from further consideration.

The abstracts of the reduced list of articles were then reviewed, checking for the following inclusion and exclusion criteria. Inclusion criteria were as follows: (1) participants completed pen-and-paper or computer-based neurocognitive tests targeting 1 or more cognitive domains; (2) participants performed a cognitively challenging sport-related task involving lower limb (ie, cutting, jumping, landing); (3) a biomechanical analysis was carried out (ie, kinematics, kinetics, electromyography). Exclusion criteria were as follows: (1) studies involving participants with recent or current musculoskeletal injuries, (2) studies involving participants with a recent or current concussion, (3) studies involving participants with an ACL tear, (4) reviews of the literature, commentary or opinion articles, case studies. Articles that met all inclusion criteria and did not meet any of the exclusion criteria were considered for final review within this paper. Full texts of records that met the eligibility criteria based on this screening process were retrieved and read by the 2 reviewers. In addition, hand searching was conducted by reviewing the bibliography of each of the retrieved full-texts, as suggested by Wright et al.[68]

Data Extraction

For each study that met the full inclusion and exclusion criteria, the following information was extracted: study design, participants, inclusion/exclusion criteria, cognitive test and sport-related task performed, methods, and cognitive and biomechanical outcome measures. The major results and conclusions of each study were summarized.

Evidence Quality and Risk of Bias Assessment

The methodological quality of the articles was evaluated using a modified version of the Downs and Black checklist,[8,20] which included 17 of the 27 original items, with an overall maximum

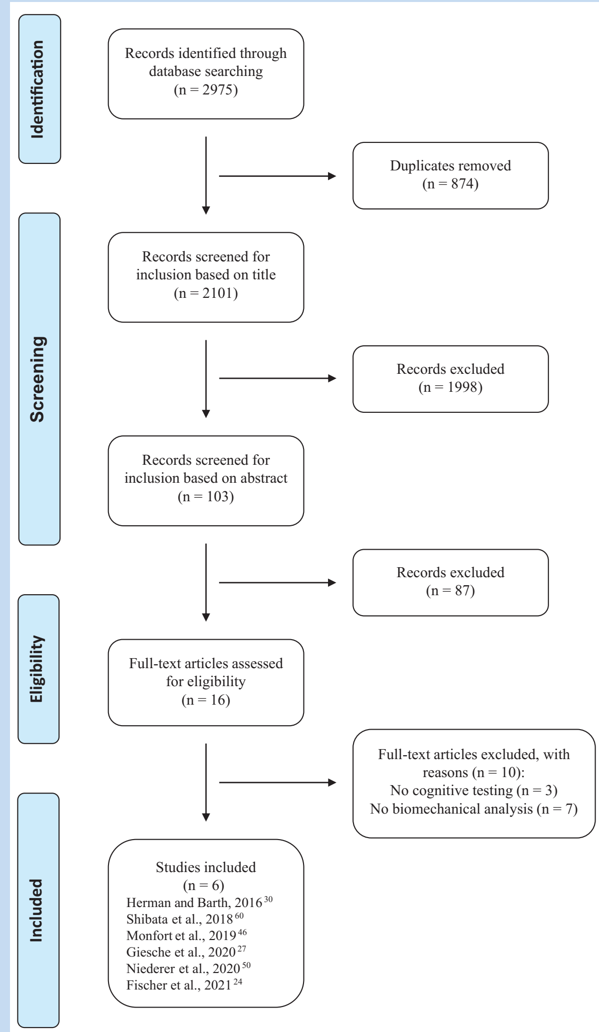

Figure 1. Flowchart for identification and selection of eligible studies for the systematic review (PRISMA). PRISMA, Preferred Reporting Items for Systematic Review and Meta-analysis.

score of 17. All studies that scored 13 or higher (>75%) were considered high-quality studies. To quantify the risk of bias within each study, all the articles selected for final inclusion in the review were assessed using the ROBINS-I checklist recommended for nonrandomized studies,[61] with a maximum score of 10. Scores of 9, 6-8, 3-5, and <3 were considered as low, moderate, severe, and critical risk of bias, respectively. Two authors independently reviewed and scored the included studies.

RESULTS

Searches of the PubMed, Web of Science, Scopus, and SciELO databases with the aforementioned search criteria returned 2975 records. After removing duplicates and screening articles for the title and abstract relevance, 16 articles underwent a full-text review. Out of these 16 articles, 6 met the inclusion/exclusion criteria and were included in the systematic review. The remaining 10 were excluded because no cognitive testing (n = 3) or biomechanical analyses (n = 7) were performed (Figure 1). Bibliography reviews did not yield any additional articles.[68]

Table 1 and the Appendix (available in the online version of this article) summarize the extracted data for each article. Sample sizes ranged from 15 to 40. Studies focused on recreational and competitive athletes or physically active young adults (age range, 20.7-27.1 years). The 6 studies used different cognitive test batteries. Two of the studies examined the performance of a 45° cutting task[46,60]; the remaining 4 studies examined some variation of a jump-landing task.[24,27,30,50] In 4 of the studies, lower limb kinematics and kinetics were analyzed using data collected with motion capture systems and force plates,[24,30,46,60] 1 of which also analyzed surface electromyography (sEMG) data.[60] The other 2 studies analyzed the center of pressure and ground-reaction force data using a capacitive pressure platform.[27,50]

Five studies found that worse cognitive performance was associated with biomechanical patterns previously linked to ACL loading and/or injury risk during cognitively challenging movements. The remaining study did not obtain any interaction between cognitive function and lower limb biomechanics.[24] Two studies divided the sample into 2 groups, based on neurocognitive performance, and then compared outcome variables between the low- and high-performance groups.[30,60] Monfort et al[46] evaluated the relationship between neurocognitive performance and knee biomechanics during single-task (nonball-handling) and dual-task (ball-handling) running sidestep tasks. Giesche et al[27] explored the relationship of neurocognitive performance with biomechanical stability and unplanned landing cost. The results obtained by Niederer et al[50] were reanalyzed by Wilke et al[65] to investigate the relationship between landing success/errors and cognitive performance. Finally, Fischer et al[24] studied the interactions of baseline cognitive function and effects of different cognitively challenging conditions on landing mechanics.

The Downs and Black[20] reduced checklist was used to critically evaluate the quality of the included studies (Appendix Table A2, available online). Herman and Barth[30] received 11 out of 17, Shibata et al[60] received 10 out of 17, Monfort et al[46] received 13 out of 17, Giesche et al[27] received 14 out of 17, Niederer et al[50] received 11 out of 17, and Fischer et al[24] received 15 out of 17. Overall, the studies considered here had good scores in reporting (mean 6.8/8) but demonstrated a lack of external validity (mean 1/2). The ROBINS-I reduced checklist was used to assess the risk of bias (Appendix Table A2, available online).[59] Herman and Barth[30] received 8 out of 10, Shibata et al[60] received 4 out of 10, Monfort et al[46] received 9 out of 10, Giesche et al[27] received 10 out of 10, Niederer et al[50] received 8 out of 10, and Fischer et al[24] received 10 out of 10. Three studies (Monfort et al,[46] Giesche et al,[27] Fischer et al[24]) demonstrated a low risk of bias, 2 studies a moderate risk of bias (Herman and Barth,[30] Niederer et al[50]), and 1 study (Shibata et al[60]) a severe risk of bias.

DISCUSSION

The purpose of this systematic review was to evaluate the association between baseline cognitive function with ACL injury-relevant knee mechanics during cognitively challenging sport movements. The following discussion of methodologies has been divided into 4 key subjects: cognitive domains assessed, effects of added cognitive load, cognitive performance ranking, and current literature limitations.

Six articles with a cross-sectional design were included in the systematic review. Out of 6 studies, 5 found that worse cognitive performance was associated with riskier biomechanics during cognitively challenging movements. This evidence is in line with previous studies confirming that lower performance in different neurocognitive domains may reduce neuromuscular control when executing cognitively challenging movements, especially when relative to external targets.[28] In particular, the time-constrained scenario of competitive sports challenges the processing of external stimuli and programming an optimal sensorimotor response, making it difficult to manage the dynamic environment and leading to harmful movement patterns.[28,53] Regarding the studies included in the present review, Herman and Barth[30] demonstrated that, compared with high cognitive performers, a low-cognitive-performance group, specifically reaction time and processing speed, exhibited higher vertical ground-reaction force, anterior tibial shear force, and increased knee abduction angle, inducing an excessive load on the ACL.[7] Analogously, Shibata et al[60] found differences in muscular activity. Low-cognitive performers, in terms of processing speed, short-term memory, and visual attention, showed higher knee extensor activation before and after the initial contact and a lower extensors-to-flexors co-contraction ratio, which may lead to an anterior shift of the tibia with respect to the femur and consequently to an increased strain force on the ACL.[7] Monfort et al[46] revealed that worse visual-spatial memory was associated with larger increases in peak knee valgus angle, potentially producing higher ligament strains,[7] when dribbling a ball. The results from Giesche et al[27] and Wilke et al,[65] obtained reanalyzing data from Niederer et al,[50] suggested that some factors that may expose athletes to higher injury risk,[27] such as the increased vertical ground-reaction force and the increased number of landing errors, were associated with reduced cognitive flexibility, working and short-term memory, and with visual perception and search. Finally, Fischer et al,[24] in contrast with other included studies, did not detect any relationship between cognitive function and harmful lower limb mechanics.

Cognitive Domains Assessed

Similar to how injurious movement patterns are the result of a variety of biomechanical variables,[10,15,32,41] it is plausible that an overall cognitive profile made up of different interacting

Table 1. Characteristics of the included studies

	Herman and Barth[30]	Shibata et al[60]	Monfort et al[46]	Giesche et al[27]	Niederer et al[50]	Fischer et al[24]
Year of Publication	2016	2018	2019	2020	2020	2021
Study title	Drop-jump landing varies with baseline neurocognition: implications for anterior cruciate ligament injury risk and prevention	The influence of differences in neurocognitive function on lower limb kinematics, kinetics, and muscle activity during an unanticipated cutting motion	Visual-spatial memory deficits are related to increased knee valgus angle during a sport-specific sidestep cut	Are biomechanical stability deficits during unplanned single-leg landings related to specific markers of cognitive function?	Acute effects of preventive warm-up exercises on modifiable risk factors for anterior cruciate ligament injuries: a 3-arm randomized-controlled crossover trial	Evaluating the spectrum of cognitive-motor relationships during dual-task jump landing
Study design	Cross-sectional	Cross-sectional	Cross-sectional	Cross-sectional	Cross-sectional	Cross-sectional
Participants	37 recreational athletes (age, 18-30 y) divided into HP and LP groups, based on cognitive testing. HP: age 21.1 ± 1.5 y; weight 68.7 ± 9.2 kg; height 1.73 ± 0.07 m. LP: age 20.8 ± 1.7 y; weight 70.1 ± 10.1 kg; height 1.72 ± 0.12 m.	15 female competitive athletes. Age 20.1 ± 1.3 y; Mass 60.6 ± 6.9 kg; Height 1.67 ± 0.07 m.	15 male collegiate club soccer players. Age 20.7 ± 2.0 y; Mass 76.5 ± 8.9 kg; Height 1.78 ± 0.07 m.	20 male individuals, physically active at the recreational level. Age 27.1 ± 4.2 y; Mass 82.4 ± 11.9 kg; Height 1.82 ± 0.07 m.	18 physically active individuals (10 females and 8 males). Age 21 ± 2 y; Mass 53 ± 10 kg.	40 female recreational or competitive athletes. Age 20.2 ± 2.6 y; Mass 64.1 ± 8.3 kg; Height 1.69 ± 0.07 m.
Cognitive tests and cognitive domains	CRI • Reaction time • Cued reaction time • Animal decoding • Visual recognition 1 • Visual recognition 2 • Symbol scanning	SDMT • Psychomotor speed • Visual short-term memory • Attention • Concentration	ImPACT • Visual memory • Verbal memory • Reaction time • Processing speed	TMT-A; CogState detection and identification task visual perception/search; Stroop color-word test; STOP-IT; Digit spans forward and backward test. • Reaction time/processing speed • Attention levels • Cognitive flexibility/working memory • Response inhibitory control • Interference inhibitory control • Verbal short-term memory	TMT-A, TMT-B • Visual search velocity • Processing speed	Letter and pattern comparison test. Letter and digit span test. Antisaccade and Stroop tests. Control Tower test. • Processing speed • Primary memory • Attentional control • Multitasking

(continued)

Table 1. (continued)

	Herman and Barth[30]	Shibata et al[60]	Monfort et al[46]	Giesche et al[27]	Niederer et al[50]	Fischer et al[24]
Movement performed	Drop-jump landing • Start: atop 30-cm box placed a distance force plate • Jump forward off the box • Land on the force plate • Jump with max effort to a second target	45° sidestep cutting • Start: atop 30-cm box placed at force plate edge • Jump forward off the box • Land on the force plate • Cutting with the dominant limb	45° sidestep cutting • Start: 6 m from the force plate • Run and 45° cut • Approach speed within 10% of the mean speed determined from practice trials	Countermovement jump • Start: bipedal stance with hands placed at the hip • Single-leg landing • Visual information depicting the landing leg • Maintain a stable single-leg stance for at least 10 s	Countermovement jump • Start: bipedal stance with hands placed at the hip • Single-leg landing • Visual information depicting the landing leg • Maintain a stable single-leg stance for at least 15 s	Drop-jump landing • Start: atop 30 cm box placed a distance force plate • Jump forward off the box • Land on the force plates • Jump with max effort to a second target
Cognitive challenging condition	Unanticipated • Secondary direction cue presented visually • 1 of 3 arrows indicating jump direction • Presented ~250 ms before initial contact	Unanticipated • Direction cue presented visually • Randomized order with other 2 task (landing and forward stepping, not analyzed)	Ball handling • Approach at the fastest speed at which participants could maintain dribbling control	Unanticipated • Visual cue after take-off • ~380 ms before landing • Landing on the correct leg	Unanticipated • Visual cue ~120 ms after take-off • Landing on the correct leg	Unanticipated • Secondary direction cue presented visually • 1 of 3 arrows indicating jump direction • Presented ~250 ms before initial contact Anticipated recall • Secondary direction told to participants before the jump • 6 dissimilar letters shown to participants for 1000 ms before the jump • Participants asked to recall the position of 1 randomly selected letter Anticipated identify/recall Secondary direction told to participants before the jump 6 dissimilar letters shown to participants, for 1000 ms, ~250 ms before contact with force plates Participants asked to recall the position of 1 randomly selected letter Unanticipated identify/recall Secondary direction cue presented visually with the randomly selected letter to recall letter and arrows, indicating jump direction, presented ~250 ms before contact, for 1000 ms

(continued)

Table 1. (continued)

	Herman and Barth[30]	Shibata et al[60]	Monfort et al[46]	Giesche et al[27]	Niederer et al[50]	Fischer et al[24]
Methods	• 16 retroreflective markers and cluster of 4 markers • 1 force plate	• 35 retroreflective • 1 force plate • 7 sEMG probes	• 58 retroreflective markers • 6 force plates	• 1 capacitive pressure platform	• 1 capacitive pressure platform	• 59 retroreflective markers • 2 force plates
Cognitive outcome measures	• Simple reaction time • Complex reaction time • Processing speed Divided into HP and LP groups based on overall cognitive outcome measures.	• Number of correct answers • Achievement rate (%) Divided into HP and LP groups based on achievement rate. The median was used as a cutoff value.	• Visual memory • Verbal memory • Reaction time • Processing speed	• Visual perception/ search • Reaction time/ processing speed • Attention levels • Cognitive flexibility/ working memory • Response inhibitory control • Interference inhibitory control • Verbal short-term memory	• Visual perception/ search • Processing speed • Time of completion	• Processing speed • Primary memory • Attentional control • Multitasking Z scores calculated for the participants' performance on each test. Z scores averaged between tests for a given cognitive domain to obtain composite scores.
Bio-mechanical outcome measures	Peak vertical ground-reaction force Peak landing-phase proximal anterior tibial shear force pKAbM pKFA Knee abduction angle Hip flexion angle Hip abduction angle Trunk flexion angle Trunk lateral bending angle	Peak in the weight acceptance phase (first 30% of stance after IC) Vertical ground-reaction force Hip flexion angle Hip adduction angle Hip internal rotation angle pKFA Knee valgus angle Hip flexion moment Hip adduction moments Knee flexion moment pKAbM CCR: relative activity of knee extensors (QUAD) to knee flexors (HAM)	Peak for the first 50 ms after initial contact Knee valgus angle (pKVA) Knee valgus moment (pKVM) Dual-task change scores (ΔpKVA, ΔpKVM)	Time to stabilization Center of pressure path length Vertical pGRF Number of standing errors Number of landing errors Unplanned landing costs	Flight time Number of standing errors Number of landing errors TTS bw TTS Fn Vertical pGRF	Peak for the first 50 ms after initial contact pKAbA pKAbM pKFA

(continued)

Table 1. (continued)

	Herman and Barth[30]	Shibata et al[60]	Monfort et al[46]	Giesche et al[27]	Niederer et al[50]	Fischer et al[24]
Results	LP group demonstrated lower CRI scores in all subtests compared with HP group LP group demonstrated adversely altered biomechanics compared with HP group 31% higher peak vertical ground-reaction force 26% higher peak proximal anterior tibial shear force 4.8° increased pKAbA 6.8° decreased trunk flexion angle	HP group demonstrated an achievement rate higher than LP group LP group demonstrated adversely altered muscle activity compared to HP group Higher QUAD activity at pre-IC (78.4±37.9% vs 40.7±21.5%) Higher QUAD activity at post-IC (137.2±54.0% vs 80.8±26.7%). Lower CCR at post-IC (28.0±10.7% vs 50.8±27.1%)	Worse visual-spatial memory associated with an increase in pKVA BH condition associated with a decrease in pKVA	Decreased postural landing stability during unplanned landings associated with lower inhibitory control Poor decision-making (number of landing errors) associated with reduced cognitive flexibility/working memory and reduced short-term memory Increases in standing errors correlated with better cognitive flexibility/working memory and short-term memory	Lower visual perception/search associated with increased number of landing errors[a] Possible association between higher pGRF and lower cognitive flexibility (nonsignificant trend)[a]	Less pKFA during anticipated identify/recall, unanticipated, and unanticipated identify/recall conditions compared to baseline Less pKFA during unanticipated identify/recall condition compared to anticipated recall condition Possible association between higher primary memory and increased pKAbA (nonsignificant trend)
Downs and Black score	11/17	10/17	13/17	14/17	11/17	15/17
ROBINS-I score	8/10	4/10	9/10	10/10	8/10	10/10

[a]Data analyzed by Wilke et al.[65]

BH, ball handling; CCR, co-contraction ratio; CRI, concussion resolution index; HAM, hamstring; HP, high performance; IC, initial contact; ImPACT, immediate postconcussion assessment and cognitive testing; LP, low performance; pGRF, peak ground-reaction force; pKAbA, knee abduction angle; pKAbM, knee abduction moment; pKFA, knee flexion angle; SDMT, symbol digit modalities test; sEMG, surface electromyography; STOP-IT, stop signal task; TMT-A/B, trail-making-test A/B; TTS bw, time to stabilization, using the participant's body weight; TTS fn, time to stabilization, using the normal force; QUAD, quadriceps.

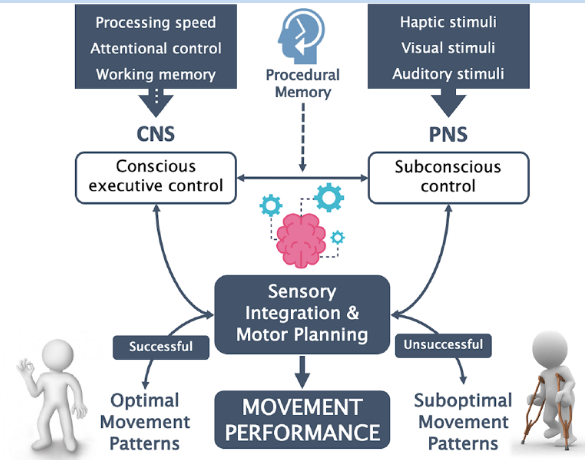

Figure 2. The cognitive process associated with movement execution. CNS and PNS activate simultaneously to process bottom-up reflexive responses to stimuli and program top-down executive function, to integrate sensory information and plan the movement execution accordingly. CNS, central nervous systems; PNS, peripheral nervous systems.

cognitive processes may contribute to impaired neuromuscular control and subsequent injury in a competitive sporting environment.[28] The cognitive processes associated with movement execution include a complex exchange of top-down executive function with bottom-up reflexive responses to excitation (Figure 2).[29,31] Thus, it is likely that not all cognitive processes relate meaningfully to changes in movement performance in a competitive setting. For example, selective attention likely plays a more significant role in managing athletic task demands than verbal fluency. Considering differences in the relevance of various cognitive domains during cognitively challenging movement performance.

In the 6 articles included in this review, 22 different tests were used to assess participants' cognitive performance. The tested domains included, in ascending order of process complexity, simple and complex reaction time, selective attention, processing speed, working memory, and multitasking.[29] Working memory was further subdivided into visuospatial and verbal memory assessments, with both subdomains including visual stimuli that had to be either spatially located for visual memory or verbally rehearsed (eg, letters and words) for the verbal one.[46] Reaction time and processing speed represent low-level cognitive processes that govern an individual's ability to respond to an incoming stimulus at a basic neurological level and would influence premovement postural adjustments as a reflex-level response.[29,62,66] Selective attention, meanwhile, functions as a "filter" of unwanted information streams when attending to a task-relevant stimulus and would benefit the athlete by directing focus toward the effective performance of some desired movement.[12,29,63] Working memory relates to the subject-specific ability to maintain and manipulate relevant information within a complex environment.[3,12,29,58] Despite evaluating different domains, all tests were presented visually and measured in a temporally demanding format (rapid responses are desired/rewarded), which is consistent with sport environments and scenarios associated with lower-extremity injuries.[67] Specifically, a key component of lower-extremity injuries in competitive sport is the temporal demand placed on athletes immediately before injury.[26-28] Cognitive demands likely depend on how quickly a response is elicited based on some input, so that they correlate with motor control in a potentially injurious scenario.[62]

Out of 6 articles, 5 identified significant cognitive-motor relationships, with all relationships sharing a common directionality: worse cognitive performance was associated with more appreciable higher-risk biomechanics during cognitively challenging movements. Among these 5 articles, the only exception to this trend was represented in Giesche et al,[27] which reported both positive and negative associations between cognitive and motor performance. Specifically, increased number of landing errors during unanticipated countermovement jumps (eg, landing on the wrong leg or both legs) was associated with reduced working memory, although, in contrast, increased standing errors (eg, landing on correct leg but touching the ground with the free leg) correlated with better working and short-term memory. Hence, overall, these articles are in line with previous findings that linked poor cognitive function with increased incidence of ACL and other lower-extremity injuries.[63,67] By understanding the scope of relationships between cognitive performance with high-risk biomechanics, these 5 articles offer initial insight into potential mechanisms behind elevated injury rates in low-cognitive performers.

The study that did not detect significant interactions between cognitive domain measures and condition-specific changes in neuromuscular control investigated the extent that different types of cognitively challenging jump landings (ie, unanticipated, visual-cognitive, working memory task demands) influenced knee mechanics and the extent that participants' biomechanical responses to these conditions were related to individual differences in cognitive function while considering several processes (ie, processing speed, primary memory, attentional control, and multitasking).[24] Given that no cognitive test is process pure (eg, attentional control loads heavily on other cognitive processes), the covariates included in the statistical model likely shared some variance.[44] The simultaneous inclusion of these covariates in the statistical models used in the study may have lessened the ability for any individual measure to associate uniquely with the reported biomechanical variables. Notably, alternate statistical models suggested processing speed was associated with knee abduction moment, although these models were inferior to the reported statistical model with respect to the Bayesian information criterion, and hence were not reported in the original study. In addition, a targeted measure of reaction time was not included in this study, which has associated with motor performance in cognitively challenging scenarios in other studies.[27,30,46]

Effect of Added Cognitive Load During Motor Tasks

Adding a cognitive load to movement assessment has proven insightful (eg, understanding the persistent effects of mild traumatic brain injuries),[23,25,34,52] and understanding individualized effects of this cognitive load on biomechanics, and in relation to baseline cognitive function, is an emerging area of research. The studies identified in the current review used tasks loading on sport-relevant cognitive processes, namely decision-making and visuospatial tracking. In fact, Hughes and Dai[35] corroborated this choice in a recent systematic review, observing changes in lower limb biomechanics as a result of decision-making and dividing attention.

Five studies relied on a form of unanticipated movement assessment. Visual cues that varied in format between studies were presented before making initial contact with the ground that participants were required to attend to, interpret accurately, and initiate a secondary movement based on the presented information. In each study where a cognitive-motor relationship was present, the findings concurred that lower cognitive function was associated with more detrimental effects due to an unanticipated directional cue. Forcing athletes to respond to directional cues limits the ability to prime the relevant neuromuscular action by shortening the time window within which they can plan the desired movement. This shortening of the response time window necessitates the adaptation of both central and peripheral nervous system-driven control strategies, mixing efficient conscious control and reflex-based movement responses.[28,62,63,67]

One study required the concurrent dribbling of a soccer ball to fulfill the dual-task paradigm for movement assessment. Such a task requires fine movement planning and motor control, as well as periodic visuospatial monitoring of the ball while performing the movement task. The finding of Monfort et al[46] that worse visuospatial memory correlated with increased dual-task cost is consistent with visuospatial monitoring being required by the athlete while dribbling a soccer ball and running. Moreover, an athlete's level of experience has been shown to influence their ability to anticipate and appropriately respond to a sports-specific stimulus during a cognitively challenging task. For example, in a competitive environment, this experience allows effective decisions and responses involving lower limb biomechanics associated with more reduced ACL injury risk than less skilled athletes.[1,22,35,38]

One study included the examination of a series of working memory and visual fixation tasks.[24] This was done in an effort to load-specific aspects of athletes' working memory, rather than recreating a sport-specific scenario. The findings indicated that the isolated working memory task did not have an appreciable effect but that the combined effects of working memory, visual fixation, and rapid decision-making led to impaired landing mechanics. Likely, the relatively achievable and discontinuous demand of the working memory task alone (memorize 6 letters, then jump, then recall the position of 1 letter) might lead to this counterintuitive finding. This result highlights the need to develop sufficiently challenging cognitive tasks to constrain attentional resources away from the desired movement.

Cognitive Performance Ranking

One consideration where the included studies differed appreciably was in the way each study chose to characterize its participants based on baseline cognitive performance measures. The decision to analyze cognitive-motor relationships on a continuum was the approach adopted by 4 of the studies included in this review and is well suited for exploring the continuous nature of individual differences in responses to task demands. In addition, taking the continuum relationships into consideration could allow for a more complex view into how cognitive domains contribute to movement performance, particularly when a relevant cognitively challenging demand is required. Herman and Barth[30] and Shibata et al[60] categorized study participants into high- and low-performance groups. Although able to test similar hypotheses, grouping the data (eg, quartiles, tertiles, or median splits) may reduce the power to detect true relationships between variables, produce effects that do not generalize to the entire sample, and/or lead to an inflated risk of biasing the data toward finding a significant group effect.[16,40]

Current Limitations

In addition to features previously discussed, the existing literature pertaining to the cognitive-motor relationship still presents significant limitations that prevent a sufficient understanding of the relevance of this interaction in the context of musculoskeletal (especially ACL) injuries in sports. For instance, small sample sizes and heterogeneous cohorts among studies have limited the effective evaluation of the whole spectrum of cognitive-motor relationships.[24,54] In assessing individual differences, a sample of 60 subjects gives roughly 80% power to detect correlations of around $r = 0.34$. Using smaller samples reduces this power and decreases the stability of any detected correlations. In fact, there are not many occasions where it is justifiable to go below a sample size of 150 to obtain stable and reliable correlations.[57] Moreover, structural equation modeling in large sample size studies, including latent variables, could help reinforce the detection of underlying cognitive-motor constructs and relationships rather than just capturing task-specific strategies.[17,39]

In addition, potential confounding factors may influence motor and cognitive function in the sport context, such as mental and physical fatigue, the biological age and maturation process of athletes, competitive sports experience and skill set, and generalizability of the relationship across different athletic movements and cognitively challenging tasks.[13,33,42,48,49] Finally, it is important to address the biasing tendency to publish primarily significant positive findings, although nonsignificant or negative results could foster and deepen the discussion about the topic.[4,21] This publication bias in favor of significant results could lead to overestimated and spurious effect sizes in literature reviews and meta-analysis.[55]

CONCLUSION

Out of 6 articles included, 5 identified significant cognitive-motor relationships, with a common directionality: worse cognitive performance was associated with an augmented injury risk profile during cognitively challenging movements.

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