Visual-Spatial Memory Deficits Are Related to Increased Knee Valgus Angle During a Sport-Specific Sidestep Cut

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Background: Identifying athletes at an increased risk of injury is a promising approach to improve the effect of injury prevention interventions; however, it requires first identifying the potential athlete-specific risk factors. Cognitive ability was recently shown to correlate with noncontact anterior cruciate ligament injury rates and lower extremity mechanics, marking an underexplored area. A better understanding of how individuals' cognitive ability is associated with neuromuscular control during sport-specific tasks may improve injury prevention.

Hypothesis: Athletes with lower cognitive performance on a standardized cognitive assessment would demonstrate greater increases in knee valgus angle and moment when performing a sidestep cut with soccer ball dribbling versus without. Visual-spatial memory was expected to demonstrate stronger relationships than reaction time or processing speed.

Study Design: Descriptive laboratory study.

Methods: Fifteen male collegiate club soccer players participated (mean ± SD: 20.7 ± 2.0 years, 1.78 ± 0.07 m, 76.5 ± 8.9 kg). Participants performed anticipated 45° run-to-cut trials with and without a dual task of dribbling a soccer ball. Peak early-stance knee valgus angle and moment for the plant limb were calculated. Participants also completed a cognitive assessment to evaluate visual memory, verbal memory, reaction time, and processing speed. These composite scores were entered as candidate predictors for a stepwise regression analysis on the dual-task change scores in lower extremity biomechanical parameters (ie, ball handling – non–ball handling).

Results: Visual memory composite score (a measure of visual-spatial memory) was the only cognitive outcome significantly associated with the change in biomechanical parameters. Each unit decrease in the visual memory composite score was associated with an increase of 0.21° ± 0.05° in peak knee valgus angle during the ball-handling task as compared with the non–ball handling task (R^2 = 52%, P = .003).

Conclusion: Visual-spatial memory was associated with neuromuscular control during a sidestep cutting task during soccer ball dribbling, with deficits in this cognitive domain being associated with increased peak knee valgus angle.

Clinical Relevance: Assessing visual-spatial memory ability may provide useful information to better understand conditions associated with impaired neuromuscular control and to potentially identify athletes at an elevated risk for musculoskeletal injury.

Keywords: cognition; dual task; knee valgus; ACL

Anterior cruciate ligament (ACL) injuries continue to present athletes with substantial short- and long-term health consequences and warrant a primary prevention approach.[1,25,38,40,51] To that end, several effective preventative interventions that target neuromuscular injury risk factors have been developed.[21,41,48,56] However, despite decades of development, the most efficacious programs reduce noncontact injury risk among female athletes by 67%,[49] a considerable achievement that also indicates room for improvement. Identifying contributing factors to the remaining noncontact injury risk that are not targeted with current prevention programs (eg, cognitive function) is within the scope of van Mechelen and colleagues'[54] established injury prevention paradigm. Improved preventative interventions that appropriately target these risk factors can then be developed and evaluated for their effectiveness.[54]

Athletes perform dynamic movements while processing a range of cognitive stimuli (eg, reacting to an opponent, remembering a play, decision making). Considering the role that cognitive abilities may play in neuromuscular control and injury risk, assessment of varied cognitive domains and biomechanical movement patterns is warranted.[52,55] In support of this concept, Swanik et al[52]

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reported that collegiate athletes with lower cognitive abilities were at an increased risk for noncontact ACL injury. Additionally, slower reaction times were associated with lower extremity sprains and strains among collegiate football players.[55] These findings of cognitive deficits being associated with increased injury risk augment recent reports indicating increased musculoskeletal injury risk after concussion, which typically degrades cognitive ability for an extended period.[9,27,45] Collectively, these studies support a potential connection between cognitive ability and musculoskeletal injury risk.

Several recent studies began to shed light into this relationship through reported associations between cognitive ability and neuromuscular control. The primary movement associated with noncontact ACL injury is knee valgus during early stance of a single-legged landing,[34,36] which often occurs when athletes are reacting to a stimulus or are otherwise devoting cognitive attention externally (eg, an opponent, ball, goal).[36] Herman and Barth[26] found that lower baseline cognitive ability was associated with these high-risk mechanics during an unanticipated drop vertical jump. The authors found that lower performance on 3 cognitive indices (ie, simple reaction time, complex reaction time, and processing speed) was associated with higher-risk mechanics, including increased knee valgus angle and moment. These findings provide a novel perspective to the numerous studies that identified higher-risk mechanics after removing athletes' ability to preplan movements.[6,8,15,44] The effects of cognitively challenging tasks on lower extremity mechanics are not limited to unanticipated movements, as others reported altered knee mechanics while attending to a ball[2,19,20,46] and performing dual-task counting tests.[17] However, only Herman and Barth[26] investigated cognitive ability as an independent variable for altered neuromuscular control, which limits the current understanding of these relationships to an unanticipated drop jump landing task and a cognitive assessment tool without domain-level resolution. Therefore, domain- and task-specific relationships between cognitive ability and neuromuscular control remain largely unknown.

To our knowledge, the relationship between cognitive ability and lower extremity mechanics during a sport-specific dual task has yet to be investigated. Specifically, we were interested in determining whether reaction time and processing speed would remain related to neuromuscular control if the task was an anticipated sport-specific dual task that emphasized different cognitive processes (eg, visual demands of dribbling a soccer ball as opposed to time-constrained decision making). Therefore, the purpose of this study was to elucidate the relationship between domain-specific cognitive ability and within-participant changes in lower extremity mechanics for an anticipated sidestep cutting task performed with and without a sport-specific dual task (ie, dribbling a soccer ball). We hypothesized that athletes with lower cognitive performance on a standardized cognitive assessment battery would demonstrate greater dual-task increases in knee valgus angle and moment, with visual-spatial memory demonstrating stronger relationships than reaction time or processing speed.

METHODS

Participants

Participants were current members of a men's collegiate club outdoor soccer team or had been members in the past 2 months. They had no history of traumatic knee or ankle injury (ie, resulting in surgery and time loss) or minor injuries (ie, hindering but not resulting in time loss) in the past 3 months that limited their participation in soccer. Participants were required to have a score $\geq$7 on the Tegner Activity Scale as well as a score $\geq$12 on the Marx Activity Scale.[42,53] Concussion history was not a specific exclusion criterion for this study, but all participants who had a prior concussion were at least 10 weeks after concussion. Number of lifetime concussions and time since most recent concussion were recorded. All participants provided institutional review board–approved informed consent before participating in the study.

Sidestep Cutting Procedure

Leg dominance was determined as the leg that the participant would use to kick a ball as far as possible. Kinematic and kinetic data were collected for the nondominant limb (ie, the plant limb in a sidestep cut maneuver) during 2 conditions: single-task non–ball handling (NB) and dual-task ball handling (BH). The nondominant limb was analyzed, as the dominant limb is used more often to handle the ball during competition[12]; thus, it was believed that the nondominant limb may be the planting limb for change-of-direction movements more often. Participants performed the NB and BH maneuvers while running and

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then cutting 45° in a single step. Participants first performed practice BH trials to determine the fastest speed at which they could properly perform the task while maintaining dribbling control. Within-participant maximum BH approach speed was used in an attempt to normalize difficulty level across participants (ie, all participants performed the task as fast as possible while maintaining control) and better reflects the speed at which the athletes may perform the tasks in competition. BH trials were performed first to ensure that the participants could maintain the maximum approach speed identified in the practice trials. For the NB trials, approach speed was matched within ±10% of the mean speed determined from the practice BH trials for a given participant. Approach speed was monitored in real time with timing gates (Smartspeed PT; Fusion Sport) placed 1 and 3 m before the force plates. Further analysis of the approach speed (at initial contact of the cutting step) and exit speed (at toe-off of the cutting step) was obtained from the motion capture data (Table 1).

Participants wore indoor soccer shoes or shoes appropriate for playing soccer on an indoor field surface. In all trials, athletes were given approximately 6 m to run or dribble toward force plates embedded in the floor. A cone placed immediately beyond the force plates was used to give a reference point to dribble and change direction—similar to evading an opponent (Figure 1). Participants were instructed to plant the nondominant leg and push off to continue in the 45° direction. Participants were required to maintain control of the ball throughout the movement for BH trials. Successful trials were those that had proper approach speeds and clean force plate contact with the nondominant (ie, plant) foot and when players were able to produce the desired maneuver with proper ball control. Eight trials were collected for each condition, with the intent of obtaining 5 acceptable trials for each condition after thorough quality control during postprocessing.

TABLE 1
Participant and Testing Characteristics

General Characteristics	Mean (SD) or n
Age, y	20.7 (2.0)
Mass, kg	76.5 (8.9)
Height, m	1.78 (0.07)
No. of concussions in lifetime	
0	9
1	2
2	1
>2	3
Approach speed, m/s	
Non–ball handling	3.73 (0.47)
Ball handling	3.86 (0.51)
Exit speed, m/s	
Non–ball handling	3.98 (0.42)[a]
Ball handling	3.87 (0.44)
ImPACT composite scores	
Visual memory, %	84.4 (8.5)
Verbal memory, %	88.7 (9.6)
Processing speed	44.8 (4.7)
Reaction time, s	0.57 (0.06)

[a] $P < .05$ for the difference between approach and exit speed in the non–ball handling condition.

Data Collection and Analysis

Retroreflective markers were placed according to a previously used full-body marker set.[32] Additional tracking markers were placed on the shoes at locations corresponding to the lateral heels and medial aspect of the first metatarsal heads to mitigate marker obstruction during BH trials. Lower body markers were arranged in a point cluster method to reduce the error introduced by soft tissue movement and better approximate rigid body segments.[3] Segment coordinate systems were defined according to Dyrby and Andriacchi[18] with the following exception: the *z*-axis for the thigh was calculated from the midpoint of the transepicondylar line to the hip joint center. Functional hip joint centers were estimated with an optimization protocol,[11] except for 3 participants who did not have functional hip joint trials for both limbs. For these participants, a regression estimation for hip joint center was used.[5] The within-participant study design is expected to mitigate the limitation of different hip joint center estimation methods on our findings. Marker data were collected at 300 Hz with an optical motion capture system (MX-F40; Vicon Motion Systems), and ground-reaction forces were sampled at 1500 Hz from 6 force platforms (4060; Bertec Corp). A matched 15-Hz fourth-order Butterworth filter was used for the marker and force data.[7,35]

Vicon BodyBuilder and MATLAB (v 2017a; MathWorks, Inc) scripts were used to calculate kinematics and kinetics of the lower extremities for each trial. Peak knee valgus angle (pKVA) and peak knee valgus moment (pKVM) were calculated given prior reports of their ability to prospectively assess noncontact ACL injury risk.[28] They were calculated for the first 50 milliseconds after initial contact of the cutting step on the basis of evidence that noncontact ACL injuries often occur within this time frame after initial contact.[34,36] Initial contact and toe-off events were identified as the first instant at which the vertical ground-reaction force exceeded or fell below 20 N, respectively. pKVM is externally defined and normalized to body weight and height.

Cognitive Assessment

Participants also completed the ImPACT cognitive assessment (ImPACT Applications, Inc).[31] This computerized test battery is widely used to evaluate cognitive symptoms after concussion, and it provides composite scores for visual memory, verbal memory, reaction time, and processing speed.[50] Briefly, the visual memory composite score is the mean percentage correct responses across a design (ie, abstract shape) memory task and a task of recalling the spatial location of illuminated X's and O's after an interference condition. The stimuli for these tasks require memory for abstract designs and spatial locations rather than for verbally rehearseable items. Thus, we interpret

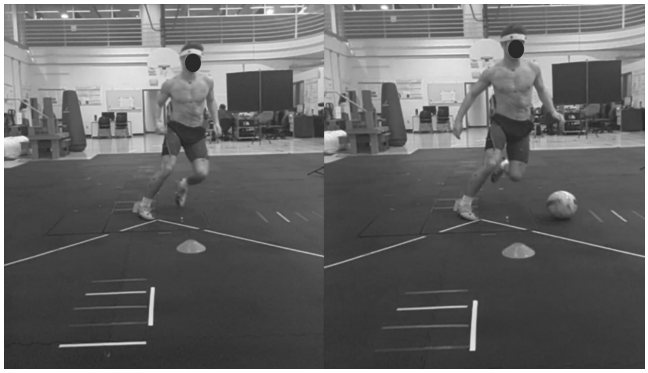

Figure 1. Sport-specific 45° sidestep cutting conditions for a left foot–dominant participant. The non–ball handling condition is shown on the left, and the ball-handling condition is shown on the right.

the visual memory composite score as a measure of visual-spatial memory. The verbal memory composite score is the mean percentage of correct responses across word memory, symbol-number matching, and letter memory tasks, the last of which contains an interference condition. The stimuli in these tasks are also presented visually, but they include letters and words that can be rehearsed verbally. The reaction time composite score is a mean response time (in seconds) of correct responses for a choice reaction test, a go/no-go task, and reaction time during the symbol-number matching task. Finally, the processing speed composite score is a weighted mean of the number of correct responses provided within the time allotted for the interference tasks from the memory tasks, where higher scores indicate better performance. Additional details regarding the tasks and calculations used for these composite scores are presented elsewhere.[30,52] The ImPACT test was consistently administered after completion of the biomechanical testing components and was performed on the same computer for all participants while using noise-reducing headphones to minimize potential distractions from any ambient noise.

Statistics

The calculated biomechanical parameters from the available trials were averaged for each condition. The dual-task change scores associated with BH (ie, BH – NB = ΔpKVA or ΔpKVM) were calculated as the dependent variables of interest for this study. Positive ΔpKVA and ΔpKVM are associated with greater knee valgus during the BH condition as compared with the NB condition. ImPACT composite scores (ie, visual memory, verbal memory, reaction time, and processing speed) were entered as candidate predictors for the change scores in lower extremity biomechanical parameters via a stepwise regression model selection method with $\alpha_{enter} = \alpha_{remove} = .15$ (Minitab 18.1). This analysis was repeated with and without including approach speed (mean between BH and NB conditions) and change in speed (approach speed – exit speed) as covariates to determine if approach or exit speed influenced the

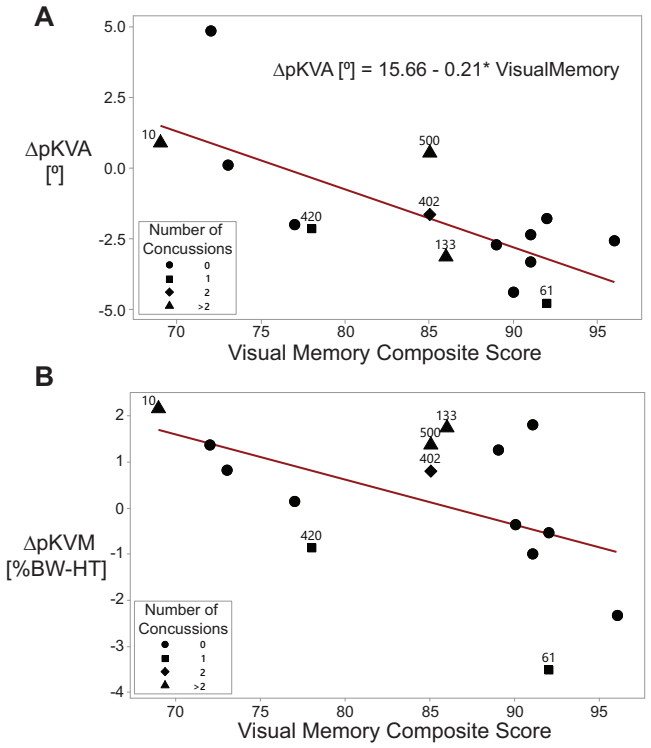

Figure 2. Linear regressions between visual memory composite score and changes in (A) peak knee valgus angle (ΔpKVA) and (B) peak knee valgus moment (ΔpKVM) from ball handling to non–ball handling conditions. Number of weeks since the most recent concussion is displayed above the data points for participants with concussion histories. Visual memory composite score was significantly associated with ΔpKVA ($P = .003$) but not ΔpKVM ($P = .049$).

relationships between cognitive ability and dual-task change scores. A secondary analysis was also performed to determine the overall effect of BH on the selected biomechanical parameters with a 2-sided paired t test. The significance level was set at $\alpha = .025$ after a Bonferroni correction for the 2 outcome parameters ($\alpha = .05/2 = .025$).

RESULTS

Of the 17 male collegiate club soccer players who participated in the study, 2 had unusable data attributed to data collection issues, leaving a total sample size of 15 participants (Table 1). Three to 5 trials were available for each condition after data processing and quality control. The primary reason for trial exclusion was bad foot strike (eg, entire foot not clearly on force plates). Of the targeted 150 trials, 143 were available for the 15 participants.

The only cognitive measure associated with the dual-task change score for BH was the visual memory composite score. Worse visual-spatial memory was associated with a greater increase in pKVA ($R^2 = 52\%$, adjusted $R^2 = 48\%$, Mallow $Cp = -0.2$, $P = .003$) (Figure 2A). Including

TABLE 2
Sport-Specific Sidestep Cutting Kinematic and Kinetic Parameters for the Test Conditions and the Change Score[a]

Parameter	Mean (SD)
pKVA, deg	
Non–ball handling	3.1 (4.2)
Ball handling	1.4 (4.4)
ΔpKVA	–1.6 (2.4)[b]
pKVM, %BW × HT	
Non–ball handling	3.2 (1.6)
Ball handling	3.4 (1.6)
ΔpKVM	0.19 (1.6)

[a]BW, body weight; HT, height; pKVA, peak knee valgus angle; pKVM, peak knee valgus moment.
[b]$P < .025$.

approach speed as a covariate had a negligible effect for the ΔpKVA outcome (R^2 = 55%, adjusted R^2 = 48%, Mallow Cp = 1.3, P = .008), did not alter the significance of the visual memory composite score regression coefficient (P = .003), and did not explain a significant amount of the variability in ΔpKVA (P = .37). Visual memory composite score was also the strongest predictor for ΔpKVM but did not reach statistical significance after controlling for multiple comparisons (R^2 = 27%, adjusted R^2 = 21%, Mallow Cp = 0.5, P = .049) (Figure 2B).

BH had a significant group effect on pKVA (P = .02), with the BH condition being associated with a decrease in pKVA (mean, –1.6°; 95% CI, –3.0° to –0.3°; Cohen d = 0.67) as compared with the NB condition (Table 2). The valgus bias of the NB condition early in stance appeared to diminish by late stance (Figure 3). No significant effect was observed for pKVM (P = .66).

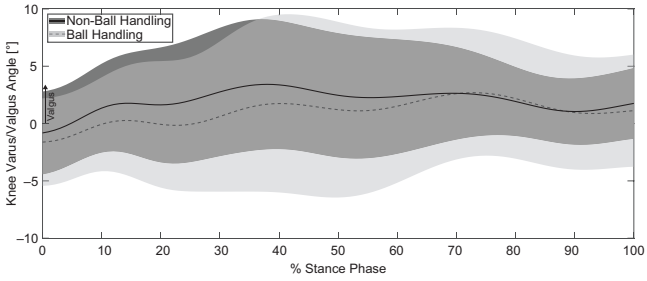

Figure 3. Frontal knee angle over stance phase of the cutting step for the non–ball handling and ball-handling sidestep cutting conditions. Lines represent group means, and the shaded regions correspond to ±1 SD.

DISCUSSION

The results of this study provide a novel contribution toward understanding how cognition is associated with lower extremity mechanics during sport, with potential implications for ACL injury risk. Using a sport-specific dual task (ie, soccer ball dribbling while making a sidestep cutting maneuver), we identified that athletes with relative visual-spatial memory deficits displayed higher-risk lower extremity mechanics when also tasked with dribbling a soccer ball. During competition, athletes only periodically direct their gaze to the ball, as they also survey their surroundings. This behavior requires visual-spatial memory resources to properly track and plan the movement of the soccer ball while coordinating motor tasks. Our findings agree with previous literature by demonstrating that cognitive ability is associated with neuromuscular control, and they extend it by demonstrating the effect during an anticipated sport-specific dual task. Ultimately, our findings build on the growing body of literature examining the relationship among cognition, musculoskeletal injuries, concussion, and motor control.

Worse reaction time and processing speed performance were previously associated with higher-risk lower extremity mechanics during an unanticipated jumping task.[26] Our current results complement these findings by suggesting that visual-spatial memory ability contributes to neuromuscular control to a greater extent than reaction time or processing speed for anticipated movements that involve navigating the environment and tracking an external object (ie, ball). Collectively, these studies provide evidence that the associations between cognition and neuromuscular control depend on the demands of the sport-specific task and athletes' ability to process the types of information involved in the task. Reaction time and processing speeds appear to be important for reactionary movements,[26] while visual-spatial memory appears particularly important for visually demanding anticipated movements. Notably, gamelike scenarios often draw on both these domains concurrently when athletes make reactionary movements while BH. Further elucidating these relationships offers a novel approach to augment existing musculoskeletal injury prevention efforts by accounting for the relevance of cognitive ability for sport-specific movements.

The ACL injury relevance of cognitive deficits requires further investigation to more completely understand the role that deficits in ≥1 specific cognitive domains have on injury risk. The estimated increase in pKVA for the lowest visual memory composite score observed in our generally healthy male cohort (~1.5°) is less than the between-participant differences in a drop vertical jump task that were prospectively associated with ACL injury risk among females.[28] However, previous modeling work suggests that this magnitude of increase in knee valgus alignment may be relevant for the ACL by decreasing the ground-reaction force threshold for injury.[13] Additionally, low visual-spatial ability may contribute to injury risk through additive or interacting effects with other previously identified factors that influence knee valgus (eg, unanticipation, fatigue) and thus warrants further investigation.

Our results indicate that visual-spatial memory best explained changes in pKVA during soccer ball dribbling, which appears to corroborate the clinical relevance of visual-spatial memory ability on noncontact ACL injury risk observed in a previous study.[52] Interestingly, the

mean visual memory composite score of the ACL-injured cohort from Swanik et al[52] (ie, 72) agrees well with visual memory composite scores that would be associated with increased pKVA through our regression analysis (ie, $\leq$76). Findings from these 2 studies support the potential for cognitive ability thresholds to identify heightened ACL injury risk that could complement existing neuromuscular assessment thresholds for isolated motor tasks (eg, drop jump landing).[28] This concept was previously demonstrated for lower extremity sprains and strains in American football.[55] A larger, more diverse population is needed to understand if sensitive cognitive thresholds exist for noncontact ACL injuries and, if so, how they may vary among a number of factors, including sport,[14,16,47] experience level,[33] sex,[10,37] and the relative effects of deficits in different cognitive domains.

The seemingly conflicting results of the slight decrease in pKVA during BH on an overall group level as compared with the increase in this variable during BH for those with lower visual-spatial ability highlight the potential importance of cognitive ability in providing a more comprehensive picture of neuromuscular control. These 2 findings in the current study suggest that most participants were effectively able to accommodate dual-task scenarios but that including a measure of cognitive ability elucidated a participant-specific relationship. The results of the current study support the inclusion of measures of cognitive ability in future studies to improve interpretation of potentially conflicting findings that could at least partially be due to differences in the sample population's cognitive ability.

Preventive screening, intervention, and rehabilitation efforts may benefit from identifying individuals with impaired visual-spatial memory, as such deficits may increase the injury risks associated with movement when engaging in sports where spatial navigation and external stimulus tracking (eg, ball, teammates, other players) are required. The results of the current study provide additional support for intervention components to address poor visual-spatial memory. Grooms et al[22] discussed the need to address visual dependency for movement in therapy and provided several methods to facilitate potentially improving visual-motor skills. These methods include stroboscopic glasses and introducing sport-relevant distractions, such as tracking a ball or reacting to a visual stimulus.[4,19,23,43] Future research is needed to evaluate the appropriateness and efficacy of these interventions for targeted injury prevention in athletes with visual-spatial memory deficits.

Our work also indicates a potential mechanism for the recent reports of increased musculoskeletal injury risk after concussion. Increased risk of lower extremity musculoskeletal injury in the first 90 days after return to play from a concussion has been reported,[9,27] with increased injury risk persisting at least 1 year after the concussion.[39] Cognitive deficits after a concussion would be predicted to be associated with higher-risk knee mechanics based on the relationships identified in our study. For example, the participant in our study who was only 10 weeks out from a concussion demonstrated the lowest visual memory composite score and an increase in pKVA while BH. This case corroborates previous findings of impaired neuromuscular function during dual-task gait that persists 2 months after concussion.[29] As our study was not designed to investigate the potential mediating role that concussion history may have in relationships between cognition and neuromuscular control, we discuss this interpretation in an exploratory context. Clinically feasible techniques that sensitively identify neuromuscular impairments in the presence of simultaneous cognitive load may provide a future opportunity to more comprehensively characterize the multifactorial risk factors for the elevated musculoskeletal injury rate of recently concussed athletes.

While this study further elucidates the associations between cognitive ability and neuromuscular control, addressing certain limitations could improve future studies of the same nature. With a long-term goal being to inform athlete-specific injury prevention efforts, expanding the sample population is necessary. Increasing the sample size and including women in particular, as well as diversifying the population by sport, experience level, and health history, will enable a more athlete-specific understanding of relationships between cognitive ability and neuromuscular control. Additionally, dribbling a soccer ball on a hard surface with indoor soccer shoes deviates from the natural setting in which the participants most commonly performed the task. Therefore, further research is needed (1) to confirm to what extent our findings extend to BH on grass while wearing cleats and (2) to analyze the dominant limb when dribbling is performed with the nondominant limb. Our findings are also limited in that the order of the sidestep cutting conditions was fixed to always have the ball-handling condition first; thus, a potential confounding role of condition order cannot be ruled out. However, post hoc analysis did not identify a significant effect of trial number for pKVA or pKVM, which mitigates this concern.

Some musculoskeletal injuries (eg, ACL tear) are also associated with altered neural activity for visual-motor processing,[24] and the addition of visual-spatial load (eg, soccer ball tracking) during coordinated actions could have a larger effect in those populations. Therefore, future research that extends this premise into injury rehabilitation efforts is needed to establish the value that it may provide in improving rehabilitation outcomes. Additionally, our protocol did not test for the potential interaction between the BH condition and an unanticipated condition. We used an anticipated task because preplanned movements are commonly performed in sports, and we wanted to isolate the potential roles of processing speed, reaction time, and memory, free of other potential confounding factors that may arise during unanticipated conditions. As reactionary movements also occur during BH, it would be important to know whether combined effects of these stimuli may alter the observed associations with specific cognitive domains. Finally, quantifying visual gaze characteristics would enable future studies to delineate the potentially confounding relationship among visual-spatial memory ability, time spent looking at or away from the ball during dribbling, and lower extremity mechanics. In light of these limitations, the current study provides new insight into relationships between domain-specific cognitive ability and neuromuscular control that may benefit future injury prevention efforts.

CONCLUSION

The effect of soccer BH during a sidestep cut movement on knee valgus angle was found to be associated with athletes' visual-spatial memory ability. These results may suggest that athletes with a diminished capacity for visual-spatial memory are less able to maintain optimal biomechanics while accommodating the demands of sport-specific tasks that require visual attention.

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