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ORIGINAL RESEARCH

Evaluating the Spectrum of Cognitive-Motor Relationships During Dual-Task Jump Landing

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Cognitive function plays a role in understanding noncontact anterior cruciate ligament injuries, but the research into how cognitive function influences sport-specific movements is underdeveloped. The purpose of this study was to determine how various cognitive tasks influenced dual-task jump-landing performance along with how individuals' baseline cognitive ability mediated these relationships. Forty female recreational soccer and basketball players completed baseline cognitive function assessments and dual-task jump landings. The baseline cognitive assessments quantified individual processing speed, multitasking, attentional control, and primary memory ability. Dual-task conditions for the jump landing included unanticipated and anticipated jump performance, with and without concurrent working memory and captured visual attention tasks. Knee kinematics and kinetics were acquired through motion capture and ground reaction force data. Jumping conditions that directed visual attention away from the landing, whether anticipated or unanticipated, were associated with decreased peak knee flexion angle ($P < .001$). No interactions between cognitive function measures and jump-landing conditions were observed for any of the biomechanical variables, suggesting that injury-relevant cognitive-motor relationships may be specific to secondary task demands and movement requirements. This work provides insight into group- and subject-specific effects of established anticipatory and novel working memory dual-task paradigms on the neuromuscular control of a sport-specific movement.

***Keywords**:* cognition, ACL, knee, sports biomechanics

Anterior cruciate ligament (ACL) injuries account for an annual cost exceeding $2 billion[1] and carry a range of comorbidities.[2–4] During sport, these injuries often occur when athletes pivot, change direction, or land from jumping.[5–7] Considering that sport is a cognitively demanding, temporally constrained environment where athletes must quickly process task-critical information, the interplay between task demands, innate cognitive function, and neuromuscular control may contribute to more comprehensively understanding ACL injury risk.

Several studies have established cognitive function as an integral ACL injury risk consideration. Athletes who sustained noncontact ACL injuries demonstrated lower cognitive function compared with matched, uninjured controls,[8] and ACL injury rates increase for athletes following concussions,[9] supporting the premise that impairments from mild brain trauma influence ACL injury risk factors.[10–15] In addition, research linking slower reaction time to lower extremity injuries[10,16] further supports the relevance of cognitive-motor function, and the ACL Research Retreat identified cognitive-motor function as a research area of interest to aid in improving primary prevention efforts.[17] Cognition is vital to ACL injury research efforts because of the connection between attentional capacity (a key aspect of cognitive function), its limits, and the consequences of overburdening it with secondary task demands. When attention is divided, cognitive interference arises, causing task performance to suffer.[18] Cognitive interference manifests during multitasking requirements inherent in sports where these injuries occur; athletes must perform movements such as a jump landing or changing direction while simultaneously attending to secondary task demands inherent in any sport.[19–26] Cognitive-motor research suggests that performing a secondary task during dynamic movement leads to adverse changes in knee mechanics.[19–26]

While the importance of lower extremity biomechanics during cognitive-motor tasks and cognitive function to ACL injury risk is clear, the link between athlete-specific cognitive function and neuromuscular control during cognitive-motor tasks is underdeveloped. Prior research reports that processing speed and reaction time were related to the knee mechanics of an unanticipated jump-landing,[22] while visual–spatial memory was associated with knee abduction changes during a sport-specific sidestep movement.[27] Muscle activation differences between high- and low-cognitive performers during an unanticipated drop sidestep have been demonstrated,[28] and participants with lower attentional control demonstrated decreased postural stability during an unplanned single-leg landing.[29] While prior studies provide support for differences in cognitive-motor function, they have investigated cognitive-motor relationships, with isolated consideration for cognitive challenges being introduced. As a result, the understanding of the spectrum of cognitive-motor relationships that are relevant to sport remains limited. This limited understanding motivates the need for a more systematic and targeted approach to elucidating the spectrum of cognitive-motor relationships in at-risk athletes during sport-specific, injury-relevant movements performed in a lab setting.

Given this knowledge gap, this study aimed to implement a systematic approach to more broadly elucidate cognitive-motor relationships that influence injury-relevant knee mechanics. Specifically, the study's purpose was 2-fold: (1) identify the effects of various cognitive demands on landing mechanics, and

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(2) investigate associations between cognitive functions and landing mechanics. We hypothesized that (1) increasing cognitive challenge complexity will be associated with increased peak knee abduction angle (pKAbA) and moment (pKAbM) and decreased peak knee flexion angle (pKFA), and (2) athletes with lower cognitive performance will exhibit greater changes in pKAbA, pKAbM, and pKFA.

Methods

Participants were eligible if they were between 18 and 30 years old, female, recreationally or competitively active in either basketball or soccer (played one of the sports at least 3 times per week or participated in either of those sports at least once a month and had prior high school varsity, college club, or equivalent competitive experience), free from lower extremity surgeries, and had not suffered a concussion or lower extremity injury within 6 months of study participation.

The study protocol involved 2 lab visits, each lasting approximately 2.5 hours. During the first visit, the participants completed baseline cognitive tests. During the second visit, the participants completed jump–land–jump movements. To identify the factors that may influence differences in cognitive performance between the visits (approximately a week apart), the participants were asked to self-report their sleep from the night before, perceived mental and physical fatigue and stress, and if they had suffered a concussion or acute head trauma since the initial visit (jump-landing session only).

The following cognitive tests were used to assess processing speed, primary memory, attentional control, and multitasking.

Processing Speed

Letter and pattern comparison tests were used, in written format, which involved indicating whether the letter or pattern pairs were the same.[30] The objective of these tests was to complete the test quickly and accurately. The measured variables were completion time and the number of correct responses. These tests' outcome variables were normalized as score = (correct number – incorrect number)/time to complete.[30]

Primary Memory

Letter and digit span tests assessed the primary memory,[31,32] where sets of 6 to 10 letters or numbers were presented aurally (digit) or visually (letter), one at a time, to the participant using E-Prime 3.0 (Psychology Software Tools, Pittsburgh, PA). After each set, the participants were required to recall the most recent 3 to 7 numbers or letters they had been given. The participants were given feedback on their performance, followed by another item set. These tests' outcome variable was the total number of letters or numbers the participant could correctly recall.[31,32]

Attentional Control

The antisaccade and Stroop tests assessed attentional control,[33,34] administered through E-Prime 3.0. In the antisaccade test, the participants were instructed to look to the opposite side of the computer screen from a flashed cue (*) in order to detect a quickly presented target item (O or Q) before it disappeared and was replaced by a pattern mask (#). This task requires suppressing the urge to look toward peripheral distractors and to instead use these cues to direct eye movements in the opposite direction to catch the target. In the Stroop test, color words were shown to the participants in font colors that were congruent with the word itself (eg, the word "green" in green font) or incongruent with the word itself (eg, the word "green" in red font). The participants were instructed to vocally respond to the font color, rather than read the word on the screen. These tests' primary outcome variables were response accuracy (both) and reaction time (Stroop only).[33,34]

Multitasking

One test assessed the participants' multitasking ability.[35] The Control Tower test consists of 3 primary tasks (number matching, symbol matching, and letter finding) and 4 secondary tasks (radar monitoring, arithmetic puzzles, color flash response, and auditory decision making). The participants completed as many primary and secondary tasks as they could for 10 minutes. The primary outcome variable was the number of primary tasks completed.[35]

Jump-Landing

During the second research visit, reflective markers were attached to the participants using double-sided tape according to a modified plug-in-gait marker set.[21] Additional tracking markers were placed bilaterally on the shoes, over the head of the first metatarsal and the lateral aspect of the calcaneus. For consistency, the same researcher placed all calibration markers on each participant. Upon recording a standing calibration trial, the markers at the medial femoral epicondyles and malleoli were removed. The participants then completed a standard warm-up of 2 sets each of 8 bodyweight squats and 5 countermovement jumps.[36]

The participants performed jump–land–jumps following an established protocol[22] under a baseline (single task) and 4 multitasking conditions (Figure 1). The participants were asked to jump in 3 secondary directions (Figure 2). Three good trials in each direction were recorded for each condition. The secondary tasks were administered using E-Prime 3.0 and a 1.5-m high-definition television screen placed approximately 5 m away from the primary landing zone. The conditions were performed one at a time. To mitigate the risk of preferentially focusing on one task, the researchers instructed the participants to "not focus on any one task in particular" and to "do their best on all tasks." The participants were allowed as many practice trials as needed to feel comfortable prior to recording the data. One to 3 trials were typically needed, depending on the condition. The conditions were block-randomized to mitigate systemic fatigue and learning effects. A trial was "good" if each foot landed within the boundary of the separate force plates and the participant jumped in the correct secondary direction immediately after landing. The kinematic data were recorded at 250 Hz using a 10-camera motion capture system (Motion Analysis Corp, Rohnert Park, CA). The ground reaction force data were recorded at 1000 Hz using 2 force plates (OPT464508-2K; Advanced Mechanical Technology, Inc; Watertown, MA).

Baseline

The participants stood atop a 30-cm box placed a distance one-half their height, away from the force plates. The researcher told the participants which secondary direction to jump before beginning. The participants were instructed to jump to the force plates and then to immediately jump "as high and as hard" as they could to one of the secondary landing zones (Figure 2). The secondary landing

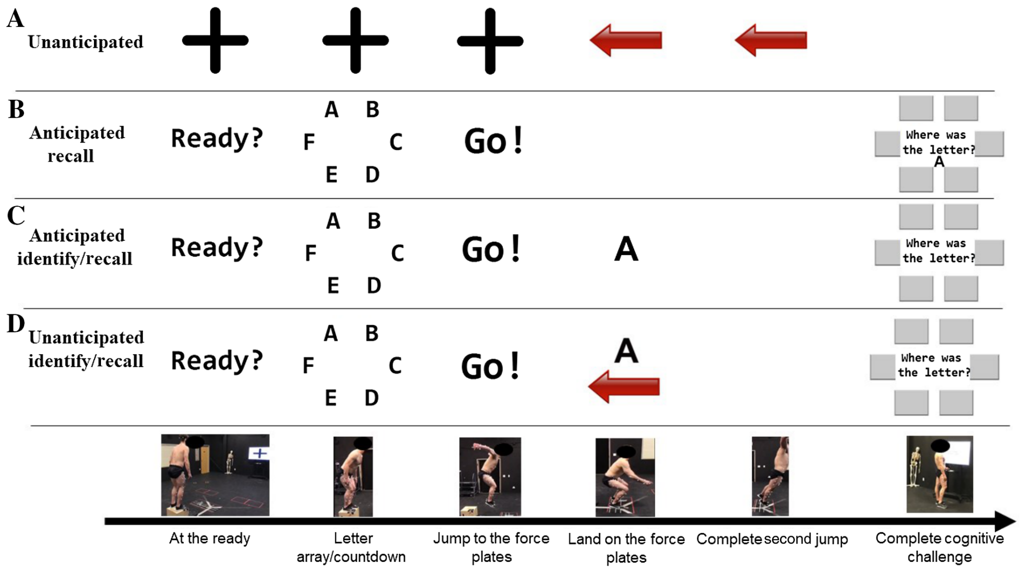

Figure 1 — The trial progression for each of the 4 dual-task jump-landing conditions. Each row corresponds to the series of images participants see on the television screen from the beginning ("At the ready") to the end ("Complete second jump/cognitive challenge") of the trial. Each column corresponds to the image presented to participants during a specific point in the trial (eg, the appearance of response letter "A" prior to landing on the force plates).

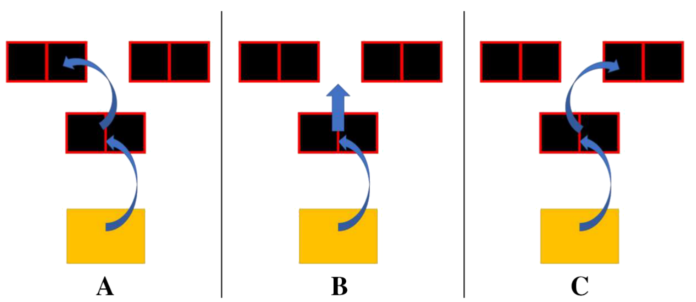

Figure 2 — Overhead schematic (not to scale) of jump directions from the box to the primary landing zone to the different secondary landing zones (A) to the left, (B) straight up, and (C) to the right.

zones to the right and left of the force plates were outlined in tape, 1 m forward and 45° to the right or left of the force plates.

The unanticipated condition (Figure 1A) challenged rapid decision making. The participants did not know the secondary jump direction before beginning the trial. They fixated on a large cross presented on a television in front of them. Approximately 250 ms prior to landing on the force plates,[22,37] an arrow appeared on the screen, indicating the secondary jump direction. Directional cues were triggered with a pressure sensor underneath the participant's left foot. This sensor was used to tune to participant-specific flight times between the top of the box and initial ground contact, such that coming off the pressure sensor started a participant-specific delay time. The randomly chosen directional cue was presented after the delay time expired.

The anticipated recall condition (Figure 1B) challenged working memory. While standing on top of the box, the participants were shown 6 dissimilar letters[31] on the monitor in front of them for 1000 ms. They then completed the jumping task. Afterward, they were asked to recall the position of one randomly selected letter from the 6 presented at the trial's beginning. Using 6 on-screen buttons, they selected the position of the letter within the array. The test recorded the accuracy of the response (correct: 1, incorrect: 0) and reset itself for another trial. The participants were not given feedback whether each response was accurate.

The anticipated identify/recall condition (Figure 1C) challenged working memory and attentional control. It followed the protocol of the anticipated recall test, with one alteration. Instead of presenting the response letter after the jump, the letter was presented ~250 ms prior to initial contact with the force plates for 1000 ms. The letter's appearance was triggered by the pressure sensor in the same manner as the directional cue in the unanticipated condition. The participants were instructed to identify the response letter while completing the jump. They recalled the position of this letter at the end of the trial, in the same manner as the anticipated recall test.

The unanticipated identify/recall condition (Figure 1D) challenged working memory, attentional control, and decision making. It followed a protocol similar to the anticipated identify/recall condition, with an added challenge that participants were presented with their directional cue, in the form of an arrow pointing in the direction of their secondary jump, directly below the response letter. Both letter and arrow were presented ~250 ms prior to initial contact, for 1000 ms, and were triggered by the pressure sensor, as previously described.

Data Analysis

Only straight-up trials were considered in this analysis. Motion capture and force plate data were filtered in Visual3D (C-Motion; Germantown, MD) using fourth-order, zero-lag, low-pass Butterworth filters with cutoff frequencies of 15 Hz.[38] Kinematic and kinetic data were calculated using an inverse kinematics model with a Quasi-Newton optimization method.[39] An inverse kinematics model was used to eliminate unrealistic translations at the hip, knee, and ankle joints and restricted the hip and knee joints to 3 degrees of freedom (rotation: flexion/extension, abduction/adduction, and internal/external rotation) and the ankle joint to 2 degrees of freedom (rotation: plantar flexion/dorsiflexion and inversion/

eversion). Joint angles were calculated using an *x–y–z* Cardan rotation sequence, corresponding with flexion/extension, abduction/adduction, and internal/external rotation. Joint moments were externally defined in the proximal segment's coordinate system and normalized to the participants' bodyweight and height. For each trial, the frame where the participant made initial contact with each force plate was defined as the first frame where the force plate reading exceeded 10 N. Custom MATLAB programs identified a 50-millisecond window, starting with the initial contact frame, for each trial and selected 3 ACL injury-relevant measures of knee mechanics, pKFA, pKAbA, and pKAbM,[7] within that window. The first 50 milliseconds following initial contact were chosen as the region of interest because prior video analysis has shown that a majority of noncontact ACL injuries occur within this time frame.[5]

The *z* scores were calculated for the participants' performance on each processing speed, attentional control, primary memory, and multitasking test. The *z* scores were averaged between tests for a given cognitive process to obtain composite scores for processing speed, attentional control (AC accuracy and reaction time), and primary memory. Composite measures were used instead of isolated test results (except for multitasking) to obtain a more robust estimate of the underlying cognitive domain.[40]

Linear mixed models tested for a fixed effect of "Condition" on pKFA, pKAbA, and pKAbM. "Participant" was entered as a random effect, and composite *z* scores were entered as covariates in the mixed-effects models. Interactions between the composite *z* scores and "Condition" were also included. If a significant fixed effect was found, follow-up Tukey pairwise tests were performed to assess pairwise differences. Effect sizes (Cohen *d*) were calculated to gauge the impacts of the dual-task scenarios on neuromuscular control. A power analysis conducted using GLIMMPSE[41] determined that a sample size of n = 40 had at least 90% statistical power to detect differences between conditions of the same or larger magnitude that were previously reported for unanticipated or cognitive challenges during jumping tasks for our selected dependent variables (4°–5° average change in pKFA, 2°–3° average change in pKAbA, 2%–3% bodyweight × height average change in pKAbM).[20,37]

Additional linear mixed models verified aspects of the protocol. Lead time, the time elapsed between stimulus presentation, and initial contact, was considered as a dependent variable to determine if the amount of time to respond to the stimulus varied between visually constrained conditions. Recall and identify/recall cognitive test performances were also considered as dependent variables to determine whether performance on these tests varied across conditions. Kruskal–Wallis tests were used to verify that self-reported measures (amount of sleep, physical and mental fatigue, and stress) did not differ between days. Significance for all statistical tests was set at $\alpha = .05$.

Table 1 Cohort Characteristics

Soccer/basketball	31/9	
Age, y	20.2 (2.57)	
Height, m	1.69 (0.07)	
Mass, kg	64.12 (8.29)	
High school experience, y	3.15 (1.15)	
College experience, y	0.44 (0.98)	
Participation, d/wk	1.26 (0.99)	
	Day 1	**Day 2**
Number of hours slept	7.4 (1.6)	7.1 (1.2)
Perceived mental fatigue	2.9 (1.4)	3.0 (1.7)
Perceived physical fatigue	2.3 (1.2)	2.7 (1.3)
Perceived stress	2.9 (1.6)	2.8 (1.4)

Note: Values are presented as average (SD).

Results

Forty participants provided written informed consent to complete this study (Table 1). The Institutional Review Board at Montana State University approved of this study's performance. No differences in self-reported sleep, mental fatigue, physical fatigue, or stress were observed between the 2 research visits (all Ps > .05; Table 1). In addition, no concussions were reported between visits. Five hundred and eighty-one out of 600 jump–land–jump trials (40 participants × 5 conditions × 3 trials) were used for analysis. Missing/excluded trials were due to participants unable to successfully complete the movement, data collection issues, or improper foot strike. The distribution of the missing/excluded trials was baseline (1), unanticipated (4), anticipated recall (0), anticipated identify/recall (2), and unanticipated identify/recall (12). The missing trials resulted in some averages being calculated with fewer than 3 trials. Average estimates for the full 40 participants were obtained for all conditions except the unanticipated identify/recall, which had estimates for 38 participants.

There was a significant "Condition" effect for pKFA (Table 2; $F = 7.72$, $P < .001$). Post hoc analysis found that, compared with the baseline condition, the participants exhibited less pKFA during the anticipated identify/recall ($P = .001$, $d = 0.33$), unanticipated ($P = .001$, $d = 0.36$), and unanticipated identify/recall conditions ($P < .001$, $d = 0.37$; Figure 3). The participants exhibited less pKFA during the unanticipated identify/recall condition compared with the anticipated recall condition ($P = .034$, $d = 0.22$). No other comparisons reached significance (Table 3; all $P > .200$). No cognitive covariates or interactions reached significance for pKFA (all $P > .200$).

Table 2 Kinematic and Kinetic Raw Values for All Jump-Landing Conditions

Early-stance landing variable	Baseline	Unanticipated	Anticipated recall	Anticipated identify/recall	Unanticipated identify/recall
pKFA, deg	58.4 (4.8)	56.7 (4.2)*	57.6 (4.1)	56.8 (4.6)*	56.7 (4.3)*,**
pKAbA, deg	10.4 (3.8)	10.4 (3.8)	10.0 (4.2)	10.3 (3.8)	10.2 (4.0)
pKAbM (bodyweight × height), %	3.0 (1.3)	3.2 (1.3)	2.9 (1.5)	3.1 (1.4)	3.0 (1.4)

Abbreviations: pKAbA, peak knee abduction angle; pKAbM, peak knee abduction moment; pKFA, peak knee flexion angle. Note: Values are presented as average (SD).
*Post hoc comparison $P < .05$ compared with baseline. **Post hoc comparison $P < .05$ compared with anticipated recall.

Regarding pKAbA, there was no "Condition" effect (Table 2; $F = 0.25$, $P = .911$). The primary memory z score as a covariate in the mixed model trended toward significance ($F = 3.00$, $P = .093$), with better primary memory associated with higher pKAbA. No other covariates or interactions reached significance (all $P > .050$).

Regarding pKAbM, there was no "Condition" effect (Table 2; $F = 1.10$, $P = .360$). No z scores reached significance as covariates for pKAbM, and no significant interactions were observed (all $P > .050$).

The average lead times between visual stimulus presentation and initial force plate contact (Table 4; $F = 0.90$, $P = .413$) and recall and identify/recall test scores (ability to accurately recall the position of the target letter) did not show a "Condition" effect (Table 4; $F = 2.61$, $P = .080$).

Discussion

This study's purpose was to identify the effects of cognitively challenging secondary tasks on landing mechanics and to quantify relationships between those secondary tasks, landing mechanics, and baseline cognitive performance measures. We hypothesized that dual-task jump landings would be associated with adverse changes in neuromuscular control, with those changes in neuromuscular control dependent on individuals' cognitive performance. The current study's findings partially support the first hypothesis, but do not support the second hypothesis. The current results suggest that athletes' responses to cognitively challenging jump-landing tasks appear to be complex and context specific.

We hypothesized that cognitive challenges would be associated with adverse changes in neuromuscular control. This hypothesis was partially supported for pKFA, but not for pKAbA or pKAbM. Significant changes in pKFA from baseline were seen for all 3 visually constrained dual-task conditions; notably, these effects were observed in pKFA across the anticipated and unanticipated conditions (Figure 1). Rather than tracking their position throughout the jump, it became necessary to rely on indirect cues of position while jumping. Small to medium effects were observed in

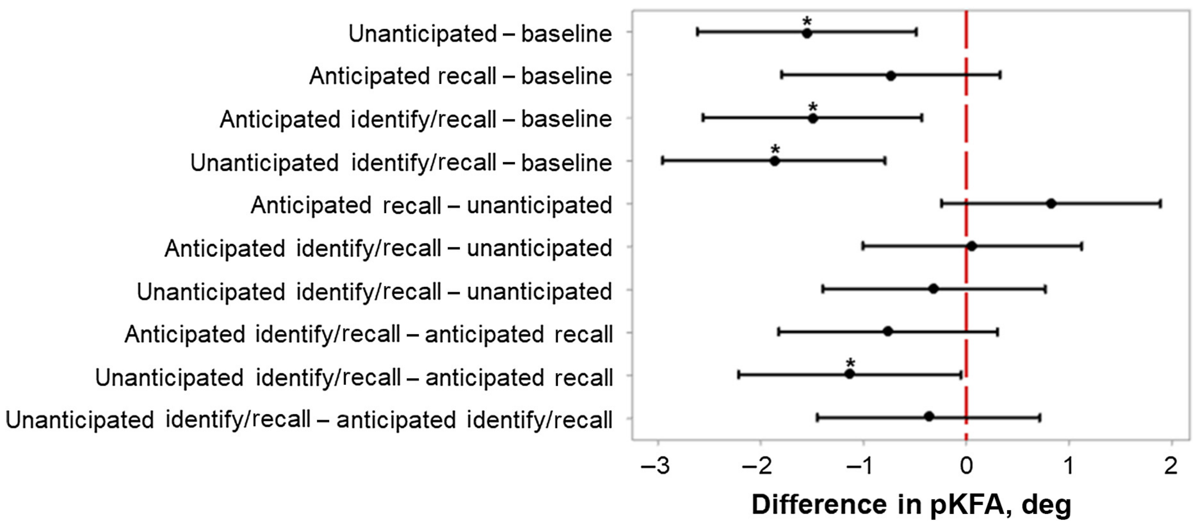

Figure 3 — The 95% CI difference in mean pKFA between conditions. When compared with the baseline, dual-task conditions with divided visual attention led to decreased pKFA during early-stance landing. CI indicates confidence interval; pKFA, peak knee flexion angle. $^*P < .05$.

Table 3 Cohen *d* Effect Sizes for Kinematic and Kinetic Results

	pKFA				pKAbA				pKAbM			
Condition	**BL**	**UA**	**REC**	**IR**	**BL**	**UA**	**REC**	**IR**	**BL**	**UA**	**REC**	**IR**
UA	0.362*				0.003				–0.150			
REC	0.168	0.211			0.089	0.086			0.016	0.153		
IR	0.331*	–0.020	–0.182		0.030	0.027	0.061		–0.083	0.059	0.091	
UAIR	0.371*	0.014	0.222*	0.033	0.047	0.044	–0.042	0.018	–0.064	0.080	–0.074	0.019

Abbreviations: BL, baseline; pKAbA, peak knee abduction angle; pKAbM, peak knee abduction moment; pKFA, peak knee flexion angle; IR, anticipated identify/recall; REC, anticipated recall; UA, unanticipated; UAIR, unanticipated identify/recall. Note: Visually constrained dual-task conditions displayed small to medium effects on pKFA compared with a visually unconstrained baseline jump landing.
$^*P < .05$.

Table 4 Lead Times and Accuracy Scores for All Dual-Task Conditions

Dual-task measure	Unanticipated	Anticipated recall	Anticipated identify/recall	Unanticipated identify/recall
Lead time, ms	279 (58)	—	272 (83)	267 (64)
Accuracy, %	—	59.16 (23.17)	55.35 (24.34)	51.51 (21.59)

Note: Values are presented as average (SD).

pKFA between the anticipated recall and unanticipated identify/recall (Table 3), lending limited support to the hypothesis that increased cognitive challenges would result in adverse changes in neuromuscular control. However, the presence of the dominant effect of visual constraint cannot be ignored. The anticipated recall condition placed no visual constraints on participants, and so it is possible these results are due, at least in part, to the same effects as detailed previously. Further investigation into different, visually unconstrained cognitive challenges is warranted.

Visual constraints likely lead to a persistent deficit in sport-specific movements, an effect that has been previously suggested.[20] Almonroeder et al[20] considered the effects of an overhead goal, a visual directional cue, and a combination of the 2 on neuromuscular control during a drop jump. They noted that, while both the presence of the overhead goal and the visual directional cue led to altered neuromuscular control compared with the baseline, there was not an appreciable difference between these conditions and the combined condition. That visual constraints influence neuromuscular control is further supported by several studies published recently.[42–44] Two studies found that the introduction of an overhead goal led to decreases in pKFA and increases in peak vertical ground reaction forces,[42,43] while the third found that varying the difficulty of a visual search task during a countermovement jump was associated with changes in postural sway during the landing phase.[29,44] While all previous studies found visual constraint effects on jump-landing performance using established paradigms, the current study expanded on previous findings by systematically introducing unique cognitive-motor tasks with different levels of complexity, finding similar effects associated with all visually constrained challenges. Given the fact that these results and prior findings suggest divided visual attention plays an important role in altering landing mechanics, decoupling the contribution of divided visual attention from other cognitive challenges becomes important for more precise interpretations and the understanding of cognitive-motor relationships.

In addition to the condition effects, we anticipated worse cognitive performance to be associated with more adverse landing mechanics (eg, higher knee abduction and less knee flexion). In support of this hypothesis, Herman and Barth[22] previously reported differences in unanticipated jump landings between high and low cognitive performers, where participants were separated based on reaction time and processing speed. However, no relationships specifically between processing speed ability and neuromuscular control were observed in the current study. Assessments of processing speed alone may not be sensitive enough to detect cognitive-motor relationships. Processing speed tests require several components of cognitive function, including visual searching, symbol comprehension, and decision making.[30] By combining processing speed and reaction time assessments, Herman and Barth[22] demonstrated that adverse changes in neuromuscular control were dependent on overall cognitive performance. By contrast, the current study found that processing speed alone was not associated with individual differences in neuromuscular control. The current data set contains 40 participants, which may cause it to be limited in its ability to fully reflect the spectrum of cognitive function that exists in the population. A data set with a larger spread of cognitive function may be better positioned to elucidate interactions between cognitive ability and cognitive-motor function.

Although previous literature observed changes in frontal plane knee mechanics arising with the introduction of unanticipated scenarios when compared with the baseline,[20] the current study observed no such effects. Two suggestions for this outcome are offered here. First, prior literature reports both the presence[20] and absence[21,37] of differences in early-stance knee abduction angle and the moment between unanticipated and anticipated conditions for jumping and cutting movements. Therefore, the lack of differences identified in this study may further motivate the value in investigating the generalizability of cognitive-motor function across sport-relevant movements. Second, all conditions that were associated with altered landing mechanics involved a visual constraint that limited participants' ability to track their landing. The current results are consistent with participants adopting a stiffer landing strategy and potentially compensating for the reduced visual feedback. It is plausible that increased knee musculature cocontraction, driven by this compensatory landing strategy, would more greatly impact knee flexion relative to abduction. Future studies that measure muscle activation patterns would be needed to confirm this theory.

There are limitations to consider when interpreting these results. One methodological concession made was the omission of an unanticipated recall condition, to allow for other subprotocols within the larger study to be completed. The kinematic and kinetic variables chosen for this manuscript represent a limitation. Noncontact ACL injuries are influenced by many different biomechanical variables at the ankle, knee, hip, and trunk. However, the authors chose a priori to restrict analysis to a select few ACL injury–relevant biomechanical variables to mitigate type I statistical error. This study's inclusion criteria limit how these findings may be extended. Biomechanical differences between males and females[21,45] and between healthy and pathological populations[46] mean caution must be taken in extrapolating these results. Including only uninjured athletes in this study may have limited the results pertaining to attentional control and reaction times, as those cognitive processes have previously been implicated as differing between injured athletes and healthy, matched controls.[8,16] Soccer and basketball players exhibit different jump mechanics[47]; the low number of basketball players who completed the study does not allow for between-sport comparisons. The working memory secondary tasks used in this study deviate from multitasking in competitive environments. However, they serve as a novel attempt to isolate cognitive processes involved in the underlying cognitive-motor relationship.

Acknowledgment

The authors have no conflict of interest to disclose.

References

1. Herzog MM, Marshall SW, Lund JL, Pate V, Spang JT. Cost of outpatient arthroscopic anterior cruciate ligament reconstruction among commercially insured patients in the United States, 2005–2013. *Orthop J Sports Med*. 2017;5(1):2325967116684776. PubMed ID: 28210655 doi:10.1177/2325967116684776
2. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Am J Sports Med*. 2016;44(7):1861–1876. PubMed ID: 26772611 doi:10.1177/0363546515621554
3. Simon D, Mascarenhas R, Saltzman BM, Rollins M, Bach BR, MacDonald P. The relationship between anterior cruciate ligament injury and osteoarthritis of the knee. *Adv Orthop*. 2015;2015:928301. PubMed ID: 25954533 doi:10.1155/2015/928301

4. Thomas AC, Villwock M, Wojtys EM, Palmieri-Smith RM. Lower extremity muscle strength after anterior cruciate ligament injury and reconstruction. *J Athl Train*. 2013;48(5):610–620. PubMed ID: 24067150 doi:10.4085/1062-6050-48.3.23
5. Krosshaug, T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med*. 2007;35(3):359–367. PubMed ID: 17092928 doi:10.1177/0363546506293899
6. Waldén M, Krosshaug T, Bjørneboe J, Andersen TE, Faul O, Hägglund M. Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: a systematic video analysis of 39 cases. *Br J Sports Med*. 2015;49(22):1452–1460. PubMed ID: 25907183 doi:10.1136/bjsports-2014-094573
7. Boden BP, Dean GS, Feagin JA, Garrett WE. Mechanisms of anterior cruciate ligament injury. *Orthopedics*. 2000;23(6):573–578. PubMed ID: 10875418 doi:10.3928/0147-7447-20000601-15
8. 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. PubMed ID: 17369562 doi:10.1177/0363546507299532
9. McPherson AL, Shirley MB, Schilaty ND, Larson DR, Hewett TE. Effect of a concussion on anterior cruciate ligament injury risk in a general population. *Sports Med*. 2020;50(6):1203–1210. PubMed ID: 31970718 doi:10.1007/s40279-020-01262-3
10. Wilkerson GB, Grooms DR, Acocello SN. Neuromechanical considerations for postconcussion musculoskeletal injury risk management. *Curr Sports Med Rep*. 2017;16(6):419–427. PubMed ID: 29135640 doi:10.1249/JSR.0000000000000430
11. Brooks MA, Peterson K, Biese K, Sanfilippo J, Heiderscheit BC, Bell DR. Concussion increases odds of sustaining a lower extremity musculoskeletal injury after return to play among collegiate athletes. *Am J Sports Med*. 2016;44(3):742–747. PubMed ID: 26786903 doi:10.1177/0363546515622387
12. Covassin T, Elbin RJ. The cognitive effects and decrements following concussion. *Open Access J Sports Med*. 2010;2010(1):55–61. doi:10.2147/OAJSM.S6919
13. Gilbert FC, Burdette GT, Joyner AB, Llewellyn TA, Buckley TA. Association between concussion and lower extremity injuries in collegiate athletes. *Sports Health*. 2016;8(6):561–567. PubMed ID: 27587598 doi:10.1177/1941738116666509
14. Herman DC, Jones D, Harrison A, et al. Concussion may increase the risk of subsequent lower extremity musculoskeletal injury in collegiate athletes. *Sports Med*. 2017;47(5):1003–1010. PubMed ID: 27544666 doi:10.1007/s40279-016-0607-9
15. Howell DR, Lynall RC, Buckley TA, Herman DC. Neuromuscular control deficits and the risk of subsequent injury after a concussion: a scoping review. *Sports Med*. 2018;48(5):1097–1115. PubMed ID: 29453743 doi:10.1007/s40279-018-0871-y
16. 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
17. Shultz SJ, Schmitz RJ, Cameron KL, et al. Anterior cruciate ligament research retreat VIII summary statement: an update on injury risk identification and prevention across the anterior cruciate ligament injury continuum, March 14–16, 2019, Greensboro, NC. *J Athl Train*. 2019;54(9):970–984. PubMed ID: 31461312 doi:10.4085/1062-6050-54.084
18. Kahneman D. *Attention and Effort*. Englewood Cliffs, NJ: Prentice-Hall, Inc; 1973:246.
19. 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. PubMed ID: 28632053 doi:10.1080/14763141.2016.1265579
20. Almonroeder TG, Kernozek T, Cobb S, Slavens B, Wang J, Huddleston W. Cognitive demands influence lower extremity mechanics during a drop vertical jump task in female athletes. *J Orthop Sports Phys Ther*. 2018;48(5):381–387. PubMed ID: 29320946 doi:10.2519/jospt.2018.7739
21. Brown TN, Palmieri-Smith RM, McLean SG. Sex and limb differences in hip and knee kinematics and kinetics during anticipated and unanticipated jump landings: implications for anterior cruciate ligament injury. *Br J Sports Med*. 2009;43(13):1049–1056. PubMed ID: 19372596 doi:10.1136/bjsm.2008.055954
22. Herman DC, Barth JT. Drop-jump landing varies with baseline neurocognition: implications for anterior cruciate ligament injury risk and prevention. *Am J Sports Med*. 2016;44(9):2347–2353. PubMed ID: 27474381 doi:10.1177/0363546516657338
23. Besier TF, Lloyd DG, Ackland TR. Muscle activation strategies at the knee during running and cutting maneuvers. *Med Sci Sports Exerc*. 2003;35(1):119–127.
24. Besier TF, Lloyd DG, Ackland TR, Cochrane JL. Anticipatory effects on knee joint loading during running and cutting maneuvers. *Med Sci Sports Exerc*. 2001;33(7):1176–1181. PubMed ID: 11445765 doi:10.1097/00005768-200107000-00015
25. Besier TF, Lloyd DG, Cochrane JL, Ackland TR. External loading of the knee joint during running and cutting maneuvers. *Med Sci Sports Exerc*. 2000;33(7):1168–1175.
26. Cortes N, Blount E, Ringleb S, Onate JA. Soccer-specific video simulation for improving movement assessment. *Sports Biomech*. 2011;10(1):22–34. PubMed ID: 21560749 doi:10.1080/14763141.2010.547591
27. 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. PubMed ID: 30986095 doi:10.1177/0363546519834544
28. Shibata S, Takemura M, Miyakawa S. The influence of differences in neurocognitive function on lower limb kinematics, kinetics, and muscle activity during an unanticipated cutting motion. *Phys Ther Res*. 2018;21(2):44–52. PubMed ID: 30697509 doi:10.1298/ptr.E9938
29. Giesche F, Wilke J, Engeroff T, et al. Are biomechanical stability deficits during unplanned single-leg landings related to specific markers of cognitive function? *J Sci Med Sport*. 2020;23(1):82–88. PubMed ID: 31628001 doi:10.1016/j.jsams.2019.09.003
30. Hambrick, DZ, Oswald FL, Darowski ES, Rench TA, Brou R. Predictors of multitasking performance in a synthetic work paradigm. *Appl Cogn Psychol*. 2010;24(8):1149–1167. doi:10.1002/acp.1624
31. Unsworth N, Fukuda K, Awh E, Vogel EK. Working memory and fluid intelligence: capacity, attention control, and secondary memory retrieval. *Cogn Psychol*. 2014;71:1–26. PubMed ID: 24531497 doi:10.1016/j.cogpsych.2014.01.003
32. Pollack I, Johnson LB, Knaff PR. Running memory span. *J Exp Psychol*. 1959;57(3):137–146. PubMed ID: 13641585 doi:10.1037/h0046137
33. Hutchison KA. Attentional control and the relatedness proportion effect in semantic priming. *J Exp Psychol Learn Mem Cogn*. 2007;33(4):645–662. PubMed ID: 17576145 doi:10.1037/0278-7393.33.4.645
34. Scarpina F, Tagini S. The stroop color and word test. *Front Psychol*. 2017;8:557. PubMed ID: 28446889 doi:10.3389/fpsyg.2017.00557
35. Redick TS, Shipstead Z, Meier ME, et al. Cognitive predictors of a common multitasking ability: contributions from working memory, attention control, and fluid intelligence. *J Exp Psychol Gen*.

2016;145(11):1473–1492. PubMed ID: 27797557 doi:10.1037/xge0000219

36. McLean SG, Lipfert SW, van den Bogert AJ. Effect of gender and defensive opponent on the biomechanics of sidestep cutting. *Med Sci Sports Exerc*. 2004;36(6):1008–1016. PubMed ID: 15179171 doi:10.1249/01.MSS.0000128180.51443.83
37. Stephenson ML, Hinshaw TJ, Wadley HA, et al. Effects of timing of signal indicating jump directions on knee biomechanics in jump-landing-jump tasks. *Sports Biomech*. 2018;17(1):67–82. PubMed ID: 28730871 doi:10.1080/14763141.2017.1346141
38. Kristianslund E, Krosshaug T, van den Bogert AJ. Effect of low pass filtering on joint moments from inverse dynamics: implications for injury prevention. *J Biomech*. 2012;45(4):666–671. PubMed ID: 22227316 doi:10.1016/j.jbiomech.2011.12.011
39. Deng HL, Gouveia W, Scales JH. An object-oriented toolbox for studying optimization problems. In: Jacobsen BH, Mosegaard K, Sibani P, eds. *Inverse Methods*. Springer; 1996:320–330. doi:10.1007/BFb0011791
40. Fischer R, Milfont TL. Standardization in psychological research. *Int J Psychol Res*. 2010;3(1):88–96. doi:10.21500/20112084.852
41. Kreidler SM, Muller KE, Grunwald GK, et al. GLIMMPSE: online power computation for linear models with and without a baseline covariate. *J Stat Softw*. 2013;54(10):i10. PubMed ID: 24403868 doi:10.18637/jss.v054.i10
42. Ford KR, Myer GD, Smith RL, Byrnes RN, Dopirak SE, Hewett TE. Use of an overhead goal alters vertical jump performance and biomechanics. *J Strength Cond Res*. 2005;19(2):394–399. PubMed ID: 15903381
43. Mok KM, Bahr R, Krosshaug T. The effect of overhead target on the lower limb biomechanics during a vertical drop jump test in elite female athletes. *Scand J Med Sci Sports*. 2017;27(2):161–166. PubMed ID: 26688032 doi:10.1111/sms.12640
44. Wilke J, Giesche F, Niederer D, et al. Increased visual distraction can impair landing biomechanics. *Biol Sport*. 2020;38(1):123–127. PubMed ID: 33795921
45. Marquez G, Alegre LM, Jaén D, Martin-Casado L, Aguado X. Sex differences in kinetic and neuromuscular control during jumping and landing. *J Musculoskelet Neuronal Interact*. 2017;17(1):409–416. PubMed ID: 28250245
46. Louw Q, Grimmer K, Vaughan C. Knee movement patterns of injured and uninjured adolescent basketball players when landing from a jump: a case-control study. *BMC Musculoskelet Disord*. 2006;7(22):1–7.
47. Taylor JB, Ford KR, Schmitz RJ, Ross SE, Ackerman TA, Shultz SJ. Biomechanical differences of multidirectional jump landings among female basketball and soccer players. *J Strength Cond Res*. 2017;31(11):3034–3045. PubMed ID: 29065078 doi:10.1519/JSC.0000000000001785