Influence of Fatigue on Cognitive-Motor Function During Unanticipated Landings

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Background: Physical fatigue and cognitive performance have been suggested as risk factors for an anterior cruciate ligament (ACL) injury, and fatigue has also been demonstrated to reduce cognitive processing. The combined effects of fatigue and lower cognitive function during cognitive-challenging movements may increase knee mechanics associated with the ACL injury risk.

Hypotheses: We hypothesized that (1) knee mechanics would be detrimentally affected by fatigue and associated with baseline cognitive function and (2) fatigue-induced deleterious changes in cognitive performance and knee mechanics would be correlated.

Study Design: Descriptive laboratory study.

Methods: A total of 22 athletes completed baseline cognitive testing. After performing maximal vertical jumps, they performed a jump-land-jump task based on unanticipated visual cues. Then, they completed a fatigue protocol including countermovement jumps, among other tasks, until the jump height decreased below 90% of their assessed maximum. Immediately after reaching the first fatigue point, they performed another set of jump-landing tasks, followed by repeating the fatigue protocol until the jump height decreased below 85% of their assessed maximum. After reaching the second fatigue point, they performed a final set of jump-landing tasks and repeated the initial cognitive assessment battery.

Results: Mixed-effects models revealed that knee flexion decreased through the fatigue protocol (baseline: 61.8°; midpoint: 61.1°; final: 60.1°; $P = .003$). Stepwise regression showed that fatigue-worsened attentional control corresponded to smaller knee abduction angles ($R^2_{\text{adjusted}} = 51.68\%$; $\beta_{\text{standardized}} = 1.16$; $P = .001$), and worse reaction time after fatigue correlated with increased knee abduction angles ($\beta_{\text{standardized}} = 0.85$; $P = .006$) after accounting for the role of attentional control.

Conclusion: Fatigue induced incremental modifications in sagittal-plane knee mechanics during an unanticipated sports movement. In addition, fatigue induced changes in cognitive function related to ACL injury–relevant knee mechanics.

Clinical Relevance: The novel findings regarding fatigue-dependent changes in injury-relevant biomechanics during cognitively challenging movements represent an extension of recent developments in understanding the role of cognition in the ACL injury risk.

Keywords: ACL; fatigue; cognition; landing; musculoskeletal injuries

INTRODUCTION

Physical fatigue has been critically debated as a possible risk factor for noncontact anterior cruciate ligament (ACL) injuries.[5,7,15] The physiological mechanisms contributing to fatigue have been classically categorized into 2 domains: those at the central (cortex) level of muscle activation and those that affect contractile function (peripheral).[23] Additionally, cognitive fatigue is characterized by an increased feeling of exhaustion and a reduction in cognitive performance during sustained demanding cognitive activities.[9] When considering the observed effect during sports practice, recent systematic video analyses of ACL injuries in professional soccer highlighted that most injuries occurred in the first half of the game, suggesting that accumulating fatigue during the match probably was not a considerable risk factor.[15,36,46] On the contrary, it has been demonstrated that a ligament failure event can occur after repetitive, harmful submaximal knee joint

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loads, each causing enough microdamage to weaken the ligament's structural integrity.[6,35,45,51,52] This alternative point of view shifts fatigue, as a risk factor, toward a complex situation involving short and intense bouts of maneuvers that gradually increase the chance of incurring an ACL tear.[35,51] This scenario usually includes a combination of knee joint compression, knee flexion moment, anterior tibial shear force, internal tibial torque, and knee abduction moment, which collectively result in the greatest loads on the ACL.[6,18]

Although fatigue may be identified as a distinct risk factor, it is unlikely to represent the primary and unique cause independently triggering the injury mechanism, as outlined above.[10] Rather, the interaction with other determinants, such as the athlete's neurocognitive function, should be considered.[42,43] In the context of sports, cognitive performance has been collectively defined as an athlete's ability to perform tasks related to the fundamental domains of functioning such as visual attention, self-monitoring, processing speed, reaction time, and dual-tasking.[8,27] As poor baseline neurocognitive performance is associated with harmful movements, deficits in cognitive subdomains such as sensory integration or attentional processing may lead to postural coordination errors and compromised lower limb patterns that pose an increased injury risk for athletes.[4,8,26,41] Added decision-making and divided attention challenges have also shown to result in deleterious effects on injury-relevant knee mechanics.[1,2,26,29] Additionally, the combined effects of fatigue and cognitive loading on lower limb mechanics during cognitive-challenging sports-relevant movements (eg, perceptual-cognitive task or unplanned conditions) may represent a worst-case scenario in terms of the ACL injury risk.[14,38,48] Almonroeder et al[3] summarized how exercise-induced fatigue might decrease cognitive processing, indicating a "supraspinal effect" of physical fatigue in addition to its well-known influence at the peripheral (muscular) level.[32] Ultimately, physical fatigue seems to have the potential to produce concurrent detrimental effects on both cognitive and motor function when performing athletic movements with high temporal constraints and applied cognitive loads, as typical during sports. Therefore, the interaction between cognition and fatigue may be an important, but understudied, area for novel clinically relevant approaches to risk screening and injury prevention.

To our knowledge, no investigations have studied the interacting effects of physical fatigue and cognitive function with respect to ACL-relevant knee mechanics. To address this knowledge gap, this study pursued a double purpose: (1) to determine the incremental effects of a sports-specific fatigue protocol on knee mechanics and how knee mechanics relate to baseline cognitive performance and (2) to reveal how fatigue-induced changes in cognitive performance relate to fatigue-induced changes in knee mechanics. We hypothesized that (1) knee mechanics measured during an unanticipated jump-landing task would be detrimentally affected by fatigue and associated with baseline cognitive function and that (2) fatigue-induced deleterious changes in cognitive performance and knee mechanics would be correlated.

METHODS

Participants

The study procedures were approved by an institutional review board (protocol No. FB040821) and met current ethical standards in human research. An a priori power analysis was conducted using GLIMMPSE (Version 3.0, SampleSizeShop.org) to obtain 80% statistical power to detect differences during unanticipated landing tasks for selected dependent variables (knee flexion angle, abduction angle and moment) with a repeated-measures design using the Hotelling-Lawley trace test, revealing a convenience sample size of 22 (see Appendix Table A1 and the GLIMMPSE supplement for means and standard deviations used in the power analysis, available in the online version of this article).[1,24,33] Eligibility criteria were as follows: age 18 to 35 years; self-reported Tegner activity score of ≥ 5; self-report of being recreationally/competitively active in sports involving jumping, running, and cutting; and ability to perform these tasks without any pain or discomfort.[16] Exclusion criteria were as follows: a history of lower extremity surgery and a concussion or lower extremity injury within 6 months of study participation.

There were 23 participants who provided institutional review board–approved written informed consent after having the study protocol (Figure 1), risks, and benefits explained to them. One participant did not complete the entire experimental trial, leaving a final sample size of 22 participants. The study protocol involved 1 laboratory visit lasting approximately 3 hours, during which the participants completed baseline cognitive testing, followed by unanticipated jump-landing tasks in alternation with a fatigue protocol and finally repeating cognitive testing after fatigue.

Cognitive Testing

Computer-based cognitive tests were administered using E-Prime (Version 3.0; Psychology Software Tools) before and after biomechanical testing to assess reaction time (RT) and attentional control (AC). These cognitive abilities were targeted because of their proposed relevance to musculoskeletal injuries.[4,8,12,28,39,43]

Simple and choice tests assessed RT. For the simple RT test, the participants looked at a computer screen and were asked to press a button on the keyboard as fast as possible upon the presentation of an image on the screen. For the choice RT test, the participants were additionally asked to distinguish between a square and a circle by pressing 2 distinct buttons in response to the complex stimulus. Both tests included 50 trials, with the delay time varying between 1 and 4 seconds across 15 different simulations. RT scores were recorded in milliseconds for both tests.[30]

Antisaccade and sustained attention to cue task tests assessed AC.[22,30,44] For the antisaccade test, participants were informed that a cue in the form of a flashing star would appear to the left or right of the screen for 300 ms and that it would be immediately followed by a target

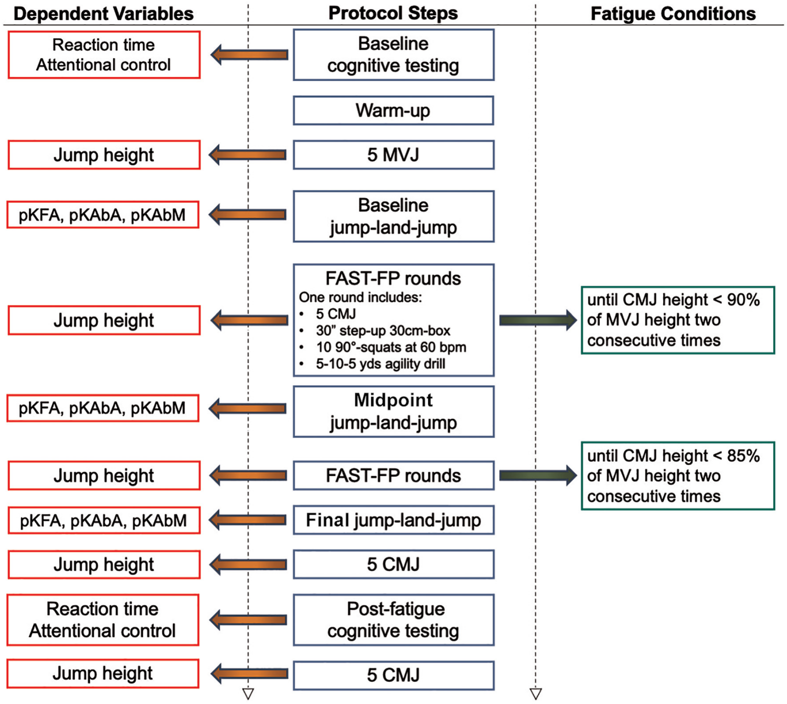

Figure 1. The study protocol. CMJ, countermovement jump; FAST-FP, functional agility short-term fatigue protocol; MVJ, maximal vertical jump; pKAbA, peak knee abduction angle; pKAbM, peak knee abduction moment; pKFA, peak knee flexion angle.

stimulus (O or Q) on the opposite side. Participants were instructed to quickly look away from the star to discern the target before it disappeared after 200 ms and was replaced by a pattern mask. They then had 5 seconds to press either the Q or the O key to indicate the identity of the target. For the sustained attention to cue task test, participants saw a fixation symbol for 2 to 3 seconds, followed by a circle cue indicating the future location of the target. This circle shrunk for 1.5 seconds and then remained for either 2, 4, 8, or 12 seconds. After this waiting interval, a distracting asterisk appeared outside the circle for 300 ms, and the target composed of a 3 × 3 letter array appeared for 125 ms and was then masked for 1000 ms. Participants were asked to indicate which of 4 possible letters (ie, B, D, P, or R) appeared in the center. AC scores were evaluated as the percentage accuracy for both tests.

Unanticipated Jump-Landing Task

Participants' lower limb dominance was defined as the leg used to kick a ball the farthest.[17] Reflective markers were attached to the participants' anatomic landmarks using a modified plug-in gait marker set.[17,24] Additional tracking markers were positioned on the shoes above the first metatarsal head and the lateral side of the calcaneus. The medial femoral epicondyle and medial malleoli markers were then removed after recording a standing trial for calibration purposes. Before starting the actual protocol, each participant performed a standardized warm-up, including 2 sets of 8 body-weight squats, 5 countermovement jumps (CMJs), and a 20-second step on a 30-cm box at a preferred pace.[24,37]

Afterward, participants performed 5 maximal vertical jumps (MVJs) to assess the maximal jump height, taken as a reference to objectively track the decrement in fatigue-induced performance. Each jump height was approximated as the right posterior iliac spine marker at the maximal vertical coordinate subtracted from that at the coordinate recorded during the standing trial. The mean height of the 3 middle jumps (excluding the lowest and the highest) was used as the individual maximal jump height.

After completing practice trials, participants performed a jump-land-jump task as a baseline condition.[24,28] The participants were asked to jump from a 30-cm box onto 2 force plates (OPT464508-2K; Advanced Mechanical Technology) and then, upon landing, jump toward an unplanned secondary direction. The secondary direction was either vertical (jumping straight up and landing on the same force plates) or toward the dominant or nondominant side (Figure 2). The secondary direction cues were administered in a randomized order in the form of an arrow that was presented approximately 250 ms before landing from the initial jump, using E-Prime (Version 3.0) on a 1.5-m high-definition television screen placed approximately 5 m away from the primary landing zone.[24] The cues were weighted 3:1 for vertical and dominant directions each and 1:1 for the nondominant direction to prevent any anticipation of the direction and efficiently collect enough trials while reducing recovery from the fatigue protocol. Only trials with a straight-up secondary direction were analyzed in the present study. Ground-reaction force (GRF) data were recorded at 1000

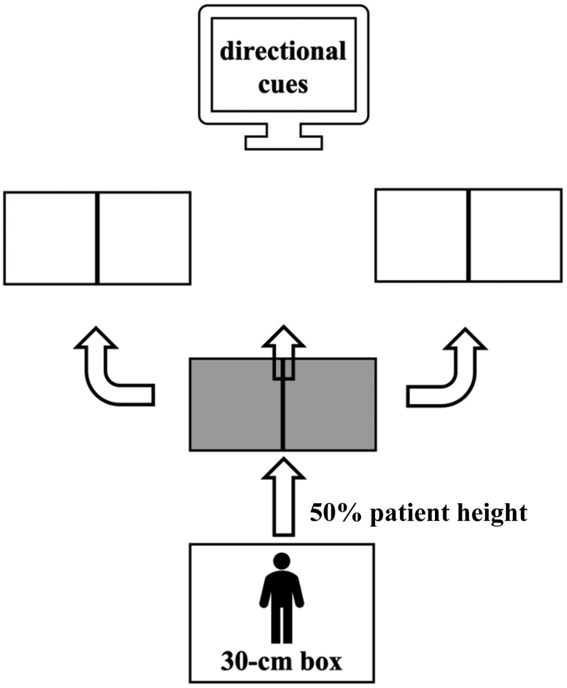

Figure 2. The unanticipated jump-land-jump task.

Hz, and marker positions were collected at 250 Hz using a 10-camera motion capture system (Motion Analysis).

Overall, 3 good trials were recorded and subsequently analyzed for the vertical direction. Good trials were defined as each foot landing on a separate force plate and the participant jumping in the correct secondary direction immediately after landing. Each participant was asked to grade the rate of perceived exertion on a 6-to-20 scale at the end of the landing tasks to assess subjective fatigue.[13]

Fatigue Protocol

After the baseline landing task, participants performed sets of a modified version of the functional agility short-term fatigue protocol (FAST-FP).[19,20,49] Each repetition of the protocol included 5 CMJs, 30 seconds of a step-up task on a 30-cm box at 200 beats/min, ten 90° squats at 60 beats/min, and a 5-10-5–yds (approximately 4.5-9-4.5-m) agility drill at maximal effort. The CMJ height was computed analogously to the MVJ during each FAST-FP set, and participants performed the fatigue protocol continuously until the CMJ height decreased below 90% of the MVJ height for 2 consecutive rounds.[20,49] Subsequently, participants completed midpoint jump landing testing using the same procedures and then additional sets of the fatigue protocol until the CMJ height decreased below 85% of the MVJ height for 2 consecutive rounds. When the MVJ height decreased below the 85% threshold, final jump landing testing was performed. We implemented this approach to objectively track the participants' fatigue status because relying on a fixed number of repetitions as an indicator of fatigue is discouraged.[5,7,15,45] Moreover, participants were repeatedly encouraged to give their best during each round of the protocol to maximize their motivation throughout the experimental session. Then, 5 CMJs were performed at the end of the fatigue protocol (experimental session of landing tasks) and another 5 following cognitive testing after fatigue to verify the degree to which physical fatigue persisted throughout the 30-minute cognitive testing session.

Data Analysis

Regarding cognitive testing, baseline and postfatigue raw scores were calculated for participants' performance on each test (expressed in milliseconds for RT tests and in percentages for AC tests). Baseline raw scores were also normalized by subtracting the mean and dividing by the standard deviation.[24] For the normalized scores, higher values correspond to faster times (for RT) and improved accuracy (for AC). The baseline-normalized raw scores were then averaged between tests for a given cognitive domain to obtain composite scores for RT and AC. Baseline raw scores were also subtracted from the postfatigue raw values to compute fatigue-induced changes in cognitive performance (ΔRT and ΔAC).

The initial landing from the jump off the box for vertical trials was the focus of the current analysis. Marker and force plate data were filtered with fourth-order, zero-lag, low-pass Butterworth filters with a cutoff frequency of 15 Hz. Kinematic and kinetic data were processed using an inverse kinematics model with commercial software (Visual3D; C-Motion) using a quasi-Newton optimization method.[24,34] Joint angles were calculated using an X-Y-Z Cardan rotation sequence, restricting the hip and knee joints to 3 rotational degrees of freedom (flexion/extension, abduction/adduction, and internal/external rotation) and the ankle joint to 2 rotational degrees of freedom (dorsiflexion/plantarflexion and inversion/eversion). Joint moments were externally defined in the proximal segment's coordinate system and normalized to the participants' body weight and height. A custom MATLAB (MathWorks) routine identified a 50-ms window after initial contact on each force plate (vertical GRF >10 N). Peak knee flexion angle (pKFA), peak knee abduction angle (pKAbA), and peak knee abduction moment (pKAbM) were extracted within this time window and defined as positive.[11] The analysis was focused on this window because most noncontact ACL injuries occur within this time frame.[31] Finally, to test the second hypothesis, baseline values of the 3 variables were subtracted from final values to obtain fatigue-induced changes in knee mechanical measures (ie, ΔpKFA, ΔpKAbA, ΔpKAbM).

Statistical Analysis

Baseline RT and AC composite scores were compared with postfatigue scores using paired *t* tests. The rate of perceived exertion values collected right after each landing task were compared using 1-way analysis of variance. After checking for data normality, 1 participant was excluded from the following analyses because of a large outlier (>3 SDs) in the biomechanical variables and the subsequent potential to influence statistical analyses.

TABLE 1
Participants' Characteristics and Cognitive Scores[a]

	Value (N = 22)	P Value[b]
Sex, male/female, n	14/8	
Age, y	22.0 ± 2.8	
Height, cm	175.9 ± 11.7	
Weight, kg	68.55 ± 12.18	
Tegner activity score	6.4 ± 1.1	
Reaction time, ms		.006
Baseline	322.8 ± 27.6	
After fatigue	337.8 ± 36.0	
Attentional control, %		.008
Baseline	96.5 ± 4.7	
After fatigue	93.2 ± 8.3	

[a]Data are presented as mean ± SD unless otherwise indicated.
[b]Paired *t* test (comparing baseline and after fatigue).

TABLE 2
Knee Mechanics Results[a]

	Baseline	Midpoint	Final
pKFA, deg	61.8 ± 5.1	61.1 ± 4.6	60.1 ± 5.2
pKAbA, deg	7.3 ± 6.6	7.1 ± 6.3	7.0 ± 6.0
pKAbM, %	3.0 ± 2.3	2.7 ± 2.0	2.8 ± 2.1

[a]Data are presented as mean ± SD. pKAbA, peak knee abduction angle; pKAbM, peak knee abduction moment (body weight × height); pKFA, peak knee flexion angle.

To test the hypothesis regarding the relationship between fatigue and baseline cognitive function on knee mechanics, we used mixed-effects models for pKFA, pKAbA, and pKAbM.[40] "Participant" was entered as a random effect and "time point" (baseline, midpoint, final) as a fixed effect for all candidate models. Baseline-normalized RT and AC scores were entered as covariates. In addition, interactions between time point and RT/AC and the interaction between the 2 cognitive domains themselves were considered in candidate models. Model selection was based on maximum likelihood estimation, and it was guided using the corrected Akaike information criterion and the Bayesian information criterion. Appendix Table A2 (available online) displays these criteria for the candidate models. The models that reduced the corrected Akaike information criterion and Bayesian information criterion consisted of random and fixed factors, as well as covariates, but not interaction effects. These models were then recomputed using restricted maximum likelihood to improve the robustness of factor estimation.[47] If a significant fixed effect was found, follow-up Tukey pairwise tests were performed to assess pairwise differences.

Additionally, to test the hypothesis that changes in cognitive performance after fatigue may correspond to fatigue-induced changes in knee mechanics, ΔAC and ΔRT were entered as candidate continuous predictors for ΔpKFA, ΔpKAbA, and ΔpKAbM in stepwise regression models. Thresholds for including/excluding terms into/from the models were set to an alpha of .15, and standardized regression (β_{std}) and adjusted R^2 (R^2adj) coefficients were computed. Minitab software (Version 19; Minitab) was used for all statistical analyses with the alpha set to .05.

RESULTS

Participants' characteristics and cognitive scores, along with differences from postfatigue values when relevant, are reported in Table 1. Cognitive composite scores worsened after fatigue for both RT (mean change, 15 ms [95% CI, 7.7 to 22.2]) and AC (mean change, –3.3% [95% CI, –4.8 to 1.7]). The MVJ height was 45.8 ± 7.8 cm, and participants performed 5.7 ± 4.3 FAST-FP sets to obtain a CMJ height below 90% of the MVJ height and another 4.7 ± 2.4 FAST-FP sets to obtain below 85% (for a total of 10.5 ± 5.4 sets). The CMJ height immediately after the final landing task corresponded to 91.6% ± 7.3% of the initial MVJ height, and the height recorded following cognitive testing after fatigue resulted in 89.2% ± 5.4%. The rate of perceived exertion values significantly increased with the progression of fatigue timepoints (baseline: 8.2 ± 1.0; midpoint: 13.1 ± 1.6; final: 15.5 ± 1.7; all $P < .001$).

Participants' knee mechanical results are reported in Table 2. A significant time point effect for pKFA was detected. The flexion angle decreased through the progression of fatigue, and subsequent pairwise comparisons revealed a significant difference between the baseline and final time points ($P = .003$). In addition, pKAbA and pKAbM showed an association with RT ($\beta_{std} = -3.18$ [$P = .031$] and $\beta_{std} = -0.94$ [$P = .053$], respectively), with worse RT performance (slower baseline RT) corresponding to larger abduction angles.

Stepwise regression for ΔpKAbA ($R^2_{adj} = 16.78\%$) revealed a significant correlation with ΔAC ($\beta_{std} = 0.83$; $P = .037$), with worse AC accuracy after fatigue corresponding to smaller changes (ie, less detrimental) in knee abduction angles. After removing a large residual point from the model, the relationship with ΔAC strengthened ($R^2_{adj} = 36.91\%$; $\beta_{std} = 1.01$; $P = .003$), and an association with ΔRT was also present ($\beta_{std} = 0.65$; $P = .039$), with decreased RT performance after fatigue (ie, slowing of RT) corresponding to larger pre-post knee abduction angles changes. When a further large residual was removed from the model, the relationship was reinforced ($R^2_{adj} = 51.68\%$) for both ΔAC ($\beta_{std} = 1.16$; $P = .001$) and ΔRT ($\beta_{std} = 0.85$; $P = .006$). ΔpKFA and ΔpKAbM did not yield significant correlations between the changes in cognitive performance.

DISCUSSION

Our findings partially confirmed our first hypothesis, showing a decrease in peak knee flexion through the fatigue protocol. The second hypothesis was partly supported, with the direction of the relationships partially counter to our hypothesis. Worse AC values after fatigue corresponded to smaller decreases in knee abduction angles, and worse RT after fatigue correlated with increases in knee abduction angles after accounting for the role of AC in models that omitted outliers. These findings provide new insight into the potential interacting relationships between physical fatigue and cognitive-motor function as they pertain to injury-relevant knee mechanics.

Regarding our first hypothesis, a recent systematic review revealed that fatigue was consistently associated with changes in movement patterns along the sagittal plane, typically decreasing hip and knee flexion at ground contact.[7] Our current results corroborate these findings by showing that pKFA, measured within 50 ms after ground contact, progressively decreased through the fatigue protocol, with a significant mean difference of 1.7° between the baseline and final time points.[6] This result is consistent with the findings of Mejane et al[38] and Borotikar et al,[14] who reported a decrease in knee flexion angles at initial contact in athletes performing a landing task before and after different muscle fatigue protocols. Collectively, our results and those of others suggest that combined effects of neuromuscular fatigue and added cognitive loads can correspond to deleterious changes in sagittal-plane knee kinematics during landing.

Still considering the first hypothesis, no significant fatigue effect emerged for either pKAbA or pKAbM when inspecting frontal-plane biomechanics. Our findings align with previous systematic reviews that reported no consistent fatigue effects on frontal-plane knee kinematics and kinetics, potentially suggesting that these variables may not be the most sensitive to changes in the injury risk in response to fatigue.[5,7,15] Nevertheless, both pKAbA and pKAbM showed an association with RT scores before fatigue, indicating that larger abduction angles and moments corresponded to slower baseline RT (ie, worse performance). This outcome reveals a critical theme when considering RT at an individual level compared with a group level. Indeed, on an average group basis, no change in pKAbA occurred during the fatigue protocol, but the individualized change in cognitive performance was associated with changes in pKAbA. This specific cognitive domain has been prospectively associated with musculoskeletal injuries in a population of collegiate football players, supporting the premise that screening RT might be a valuable tool to identify athletes at risk of sustaining strains or sprains.[50] Similarly, Swanik et al[43] revealed that 80 collegiate athletes who experienced a noncontact ACL injury showed worse RT scores (along with other cognitive subdomains) compared with matched healthy controls. Cumulatively, these 2 studies reported a mean change between injured groups and controls ranging from 8 to 40 ms. Therefore, our result (mean change of 15 ms) falls within this interval, suggesting that RT decreases after the fatigue protocol can be considered clinically meaningful. Furthermore, several studies have indicated a possible relationship between decreased RT and harmful lower limb mechanics (ie, higher peak GRF, peak proximal anterior tibial shear force, knee abduction angle/moment and reduced knee flexion angle).[4,8,25,28,41] Our results corroborate this evidence and extend it by showing that worse baseline RT scores corresponded to increased harmful knee mechanics in the frontal plane throughout the fatigue progression. This finding suggests that lower performance in this neurocognitive domain may potentially decrease athletes' ability to integrate stimuli and safely plan movements in dynamic sports environments, and this relationship could be influenced by fatigue incurred during competition.[3]

The observed relationship between fatigue-induced changes in cognitive function and injury-relevant knee mechanics provides a novel perspective on risk factors for an ACL injury. Larger fatigue-induced decrements in AC corresponded to smaller changes in knee abduction angles. This relationship is counter to our hypothesis that worse AC would be related to deleterious changes in pKAbA. An association with RT was present when excluding 1 influential data point. However, this relationship was not confirmed when running isolated bivariate regression models with only ΔRT and ΔpKAbA included. Therefore, the role of ΔRT was only present after accounting for variance explained by ΔAC, supporting the potentially more prominent role that AC plays in explaining fatigue-induced abduction angle variations. AC has been defined as the cognitive subdomain responsible for focusing on relevant information while ignoring other nonrelevant stimuli, as during the dual-task paradigm.[24,25,27] Interestingly, our findings suggest that patients with larger decrements in AC performance due to the fatigue protocol exhibited less harmful changes in frontal-plane knee mechanics. This relationship could be related to the larger fatigue-induced AC decrements occurring in participants with higher baseline AC scores, as documented in a follow-up correlation analysis ($r = -0.62$; $P = .004$) (Appendix Figure A1, available online). These decrements are somewhat consistent with cognitive performance decrements being most pronounced in high cognitive performers,[21] with a plausible interpretation of our findings being that high baseline AC performers increased their attention on the motor task in the presence of AC decrements to support moving successfully and/or safely.[21] Therefore, high AC scores during highly dynamic unanticipated maneuvers may increase irrelevant information processing and, subsequently, total processing time, preventing optimal movement planning and leading to potentially harmful biomechanics.[8] To our knowledge, this is the first investigation specifically targeting AC in association with high-risk biomechanical changes; thus, our findings concerning AC may represent a novel principle regarding this cognitive-motor relationship, which warrants further investigation.

Some limitations must be considered. First, the cross-sectional nature of the study design is not able to establish the clinical relevance of our findings in the context of a prospective association with the ACL injury risk; thus, future research in this area is needed. The double-leg landing task, as well as the limited set of injury-relevant kinematic and kinetic variables selected in this study (not including, for example, anterior shear forces), represents a limitation. However, this selection was made a priori to limit type I statistical errors and was based on previously published literature. Moreover, the study's sample size and inclusion criteria limit the generalization of the findings, and sex differences have not been investigated, even though a supplemental follow-up analysis revealed that adding sex as a mixed effect did not affect the statistical significance of our findings. In addition, monitoring the participants' internal load (eg, heart rate) during the fatigue protocol may have provided more precise information about the physiological response to the exercise. Finally, the cognitive performance assessment, as well as the unanticipated jump-landing task, was carried out using standardized testing procedures that may not simulate the actual cognitive loads of athletes when dealing with cognitively challenging gamelike situations. Despite these limitations, the findings provide new insight into the interaction between physical fatigue and cognitive-motor function relevant to ACL injury risk factors.

CONCLUSION

During an unanticipated jump-landing task, knee flexion decreased through the fatigue protocol, but no significant fatigue effect emerged when inspecting frontal-plane biomechanics. In addition, deteriorated AC corresponded to smaller fatigue-induced knee abduction angles, and reduced RT correlated with increased knee abduction angles after accounting for the role of AC. Physical fatigue can interact with cognitive-motor function as measured by knee mechanics associated with ACL injuries, which highlights a multifactorial perspective to injury prevention strategies.

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