Relationships between Patient-Reported Outcomes and Predictors of Second ACL Injuries during Unanticipated Jump Landings

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ABSTRACT

MONFORT, S. M., F. AFLATOUNIAN, P. D. FISCHER, J. N. BECKER, K. A. HUTCHISON, J. E. SIMON, and D. R. GROOMS. Relationships between Patient-Reported Outcomes and Predictors of Second ACL Injuries during Unanticipated Jump Landings. *Med. Sci. Sports Exerc.*, Vol. 57, No. 4, pp. 840–848, 2025. **Background:** Reactive and external visual–cognitive demands are prevalent in sport and likely contribute to anterior cruciate ligament (ACL) injury scenarios. However, these demands are absent in common return-to-sport assessments. This disconnect leaves a blind spot for determining when an athlete can return to sport with mitigated re-injury risk. **Purpose:** To characterize relationships between patient-reported outcome measures (PROMs) and cognitive-task interference (i.e., cognitive demands exacerbating neuromuscular impairments) for biomechanical predictors of second ACL injuries during jump landings that involved rapid unanticipated decision making. **Methods:** Thirty-six persons following primary ACL reconstruction (ACLR; 26 females/10 males, 19.8 ± 1.8 yr; 1.71 ± 0.1 m; 69.6 ± 12.8 kg, 1.5 ± 0.6 yr post-ACLR; Tegner: 6.8 ± 1.8) participated. PROMs of ACL-RSI and the Forgotten Joint Score-12 Knee (FJS-12) were selected to assess altered psychological state (e.g., confidence, attention toward knee). Jumping tasks under anticipated and unanticipated secondary jump directions were performed. Biomechanical variables were dual-task changes (unanticipated − anticipated) in 1) uninvolved limb hip rotator impulse (DTC_Uni-HRot_Imp), 2) asymmetry of knee extensor moment at initial contact (DTC_KEM_Asym), and 3) range of involved knee abduction angle (DTC_KAbA_Range). Regression models tested for relationships between PROMs and the dual-task change in biomechanical variables. **Results:** ACL-RSI (DTC_Uni-HRot_Imp (P < 0.001)) and FJS-12 (DTC_KAbA_Range (P = 0.001)) had significant relationships with dual-task change in the opposite direction as expected (worse PROM ➔ less dual-task change). A follow-up analysis indicated that dual-task change was inversely correlated with the baseline estimates for kinetic biomechanical variables (less risky single-task biomechanics ➔ greater dual-task change for Uni-HRot_Imp and KEM_Asym). **Conclusions:** The collective results are consistent with higher functioning participants (better PROMs) who also demonstrate desirable biomechanics during single-task conditions being prone to demonstrating the greatest risk-associated DTC in unanticipated scenarios. **Key Words:** COGNITIVE–MOTOR FUNCTION, BIOMECHANICS, RETURN-TO-SPORT, ACLR

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High rates of second anterior cruciate ligament (ACL) tears (~20%–30%) (1,2) persist in young athletes following ACL reconstruction (ACLR) despite passing common return-to-sport (RTS) criteria. Cognitive–motor scenarios (i.e., concurrent motor and cognitive demands) are ubiquitous in sport and overrepresented in observational injury scenarios for primary and second ACL injuries (e.g., player directing visual attention to an opponent) (3–5); however, they remain absent in common ACLR RTS assessments (6–12). Insight into the clinical relevance of cognitive–motor function is provided by the substantial literature suggesting that cognitive demands, particularly unanticipated/reactive scenarios that require rapid decision making, elicit risky biomechanics during athletic movements (13–17).

Central capacity sharing theories are often used to interpret cognitive–motor interference, where individuals are believed to have limited mental resources that are used as they perform concurrent motor and/or cognitive tasks (18–20). As task-related competition for these resources leads to resource scarcity, performance declines are expected in one or more of the tasks. The importance of considering cognitive–motor scenarios following ACLR is emphasized by neuroplastic and

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neurophysiological alterations following ACLR, which are linked to arthrogenic muscle inhibition and neural inefficiency following ACLR (21–24). In the context of central capacity sharing models, these neurological effects may lead to more rapid depletion of limited attentional resources and predispose ACLR patients to cognitive–motor interference in the rich cognitive–motor sport environments (20,25). Notably, ACLR patients may demonstrate desirable physical performance on many current RTS tests (e.g., hop tests) in part by leveraging cognitive compensatory strategies; however, this compensation strategy is only effective during scenarios with low additional cognitive load (e.g., single-task environments), which are not representative of sport environments. Therefore, considering cognitive–motor function following ACLR may enable the detection of movement impairments that otherwise are being masked by increased cognition.

To characterize cognitive–motor integration deficits specific to ACLR, dual-task changes (DTC) or percent changes between a cognitive–motor condition and motor condition challenge of rapid decision making are often calculated. This approach is well established across many movements and populations (e.g., DTC in gait speed in older adults) (26,27), including clinical assessments of function following ACLR using neurocognitive adaptations of function tests (28,29). Calculating DTC that result from the inclusion of sport-relevant neurocognitive challenges, such as a rapid decision making and visual working memory, may quantify RTS-relevant maladaptive compensatory strategies. Such an approach is a promising area to augment RTS decision making to contribute to combating the high risk of re-injury following ACLR.

No prior research has linked cognitive–motor performance to outcomes following ACLR (e.g., re-injury risk, patient-reported outcome measures (PROMs)). Furthermore, prior research has yielded mixed, sometimes conflicting, results regarding the relationship between PROMs of various functional and psychological constructs with second ACL injury risk and high-risk biomechanics. Higher scores on the ACL-Return to Sport after Injury (ACL-RSI), which is commonly interpreted as better psychological readiness, have been related to a lower risk of a second ACL injury (30). Less improvement over time on the ACL-RSI was also related to an increased risk of a second ACL injury (31). In contrast, Zarzycki et al. (32) found that female athletes with higher ACL-RSI scores were associated with an increased risk of a second ACL injury. Other studies have also implicated high knee-related confidence with increased second ACL injury risk (33,34). These conflicting relationships between PROMs and the directionality of their associations with second ACL injury risk exist alongside studies that generally indicate ACLR patients with increased kinesiophobia demonstrate higher-risk knee mechanics (35–37). These findings align with evidence for high self-reported fear predicting second ACL injuries (38); however, the clarity of the collective results is somewhat limited by inconsistent choice of biomechanical outcome variables across studies. The variability in these findings may suggest that there are factors unaccounted for that need to be elucidated to more completely understand the relationship between PROMs and second ACL injury risk. One limitation of prior research regarding associations between PROMs and injury-relevant mechanics is that the biomechanical testing has consistently been done in isolated conditions that only involve motor demands (e.g., a jumping task) without additional cognitive challenges.

The relationship between PROMs and biomechanical predictors of second ACL injuries in response to cognitive–motor challenges is currently unknown, but may be a missing component to help explain previous mixed findings regarding PROMs and injury risk and injury mechanics. By accounting for this missing component, new insight to improve ACLR RTS may be gained. Therefore, the purpose of this study was to characterize relationships between PROMs and cognitive–motor interference for biomechanical predictors of second ACL injuries (e.g., frontal plane knee motion) during jump landings that involve rapid decision making (i.e., unanticipated). We hypothesized that worse scores on PROMs would be associated with greater cognitive–motor interference (i.e., larger dual-task induced impairments in biomechanical predictors of second ACL injury) during a jump landing task.

METHODS

Participants. Individuals 14–24 yr old having been cleared to return to unrestricted activity following a primary ACLR and within 2.5 yr from their ACLR surgery were recruited for the study. Exclusion criteria included any lower extremity surgery before ACLR and lower extremity injury or concussion within 1 year before participation. All participants signed an IRB-approved written informed consent (and assent for minors) before participation in the study. Data from 37 participants were collected; however, data from one participant were excluded due to an inability to adhere to the unanticipated jump landing protocol (i.e., notable pause upon landing). A description of the remaining 36 participants is provided in Table 1.

Patient-reported outcome measures. ACL-RSI (39) and the Forgotten Joint Score-12 Knee (FJS-12) (40,41) were selected to assay psychological readiness and joint awareness related to knee (dys)function, respectively. Psychological readiness (ACL-RSI) was chosen because of its relationship (30,31), albeit variable (32,42), with second ACL injury risk and the basis that self-reported confidence may relate to how individuals respond to moving in cognitively challenging situations. FJS-12 was selected for a similar reason, proposing that athletes focusing attention toward their knee may influence attentional resources available to perform in cognitive–motor scenarios. Lower scores on the PROMs indicate worse outcomes. Tampa Scale of Kinesiophobia (TSK-11) (43), Knee injury and Osteoarthritis Outcome Score (KOOS) subscales (44), and International Knee Documentation Committee subjective knee evaluation form (IKDC) (45) were also collected to describe the sample population but excluded from analyses

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TABLE 1. Participant demographic, clinical, and activity information.

Age, yr	19.8 (1.8)
Sex	26 F/10 M
Mass, kg	69.6 (12.8)
Dominant limb	31 R/5 L
ACLR information	
ACLR limb	20 R/16 L
ACLR graft type	
Patellar tendon, *n* (%)	9 (25)
Hamstring, *n* (%)	12 (33)
Quad tendon, *n* (%)	14 (39)
Other, *n* (%)	1 (3)
Time since ACLR surgery, yr	1.5 (0.6)
Physical and sport activity	
Tegner score	6.8 (1.8)
Marx activity score	10.6 (4.1)
Primary sport[a]	
Down-hill skiing, *n* (%)	13 (36)
Soccer, *n* (%)	6 (17)
Basketball, *n* (%)	6 (17)
Volleyball, *n* (%)	3 (8)
Running, *n* (%)	3 (8)
Weight lifting, *n* (%)	2 (6)
Other, *n* (%)	3 (8)

Values are presented as mean (SD) or *n* (%).
[a] Does not reflect multiple sports played by some participants.

to reduce collinearity issues. A summary of all PROMs for the sample population is provided in Figure 1.

Cognitive–motor interference assessment. Biomechanical testing was performed as part of a larger research study that aimed to decouple the effects of constraining visual gaze versus rapid decision making regarding the biomechanical deficits following ACLR. Specific to the current research question, adaptations to the jump–land–jump task of the Landing Error Scoring System (46) were used to assess cognitive–motor interference, which was characterized as changes in injury-relevant biomechanics in response to unanticipated (i.e., rapid decision making) constraints. Briefly, the jumping task involved participants self-initiating the initial jump off a 30-cm-tall box, landing on force plates that were 50% of the participant's height away from the box, and then immediately performing a second maximal effort jump after their initial landing.

We implemented several conditions of the jump–land–jump movement to target cognitive–motor interference. An anticipated baseline consisted of the standard movement with participants able to look at the landing area for the initial landing. Three unanticipated versions of the task were also performed that involved a directional cue being presented shortly before the initial landing that informed participants of a secondary jump direction (randomly chosen between: straight up, 45° to the left, 45° to the right). As all these conditions included rapid decision making, they were included in the current analysis to leverage the larger pool of evidence to investigate the research question. The unanticipated conditions were as follows: VUF, visual unanticipated cue presented via arrows on a screen 250 ms before the initial landing; AUD, auditory cue ("Up," "Left," or "Right") that was played with participants able to look at the landing area; and AUF, the auditory cue with participants' visual gaze restricted to a fixation cross on a screen in front of them (Fig. 2). Manipulating visual gaze and the stimulus modality was motivated by prior reports of overhead targets influencing lower extremity biomechanics (47,48) and ACLR individuals increasing reliance on visual information (21,22,49–52). The directional cue presentation was facilitated by force-sensitive resistors under participants' feet on the 30-cm box that indicated the instant they no longer had contact with the box during the initial jump. After familiarizing participants with the jump–land–jump movement and before collecting biomechanical data, participants performed five jumps that were used to calculate the subject-specific flight time and coordinate the presentation of the directional cues to be 250 ms before initial contact for the first jump (53). Because the auditory cues were brief audio files that lasted ~100 ms, their presentation was initiated 350 ms before initial contact to attempt to align the available time to react across cue modalities to be 250 ms. Directional cue timing was confirmed via *post-hoc* analysis (Supplemental Table 1, Supplemental Digital Content, http://links.lww.com/MSS/D134). Five good trials (feet landing on separate force plates, second jump occurring immediately after initial landing in the correct secondary jump direction) for the straight-up secondary jump direction were used for each condition to generate averages for biomechanical variables of interest.

Biomechanics data collection and processing. Motion capture data were recorded from 10 cameras (Motion Analysis Corporation, Rohnert Park, CA) and five force plates (OPT464508-2K; AMTI; Watertown, MA) collecting at 250 and 1000 Hz, respectively. A full-body markerset consisting of 75 reflective markers was used. The markerset followed a point-cluster distribution of markers on the thighs and shanks to cover a large area of the respective segments to mitigate soft tissue artifact during pose estimation of the segments (54). A

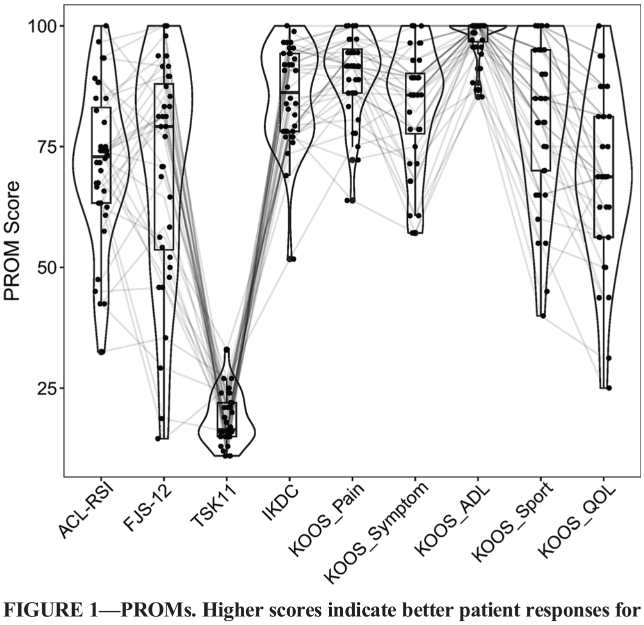

FIGURE 1—PROMs. Higher scores indicate better patient responses for all PROMs except TSK-11, where higher scores indicate greater fear. Lines between datapoints connect the same participant across PROMs. KOOS subscales include pain, activities of daily living (ADL), sport, and quality of life (QOL).

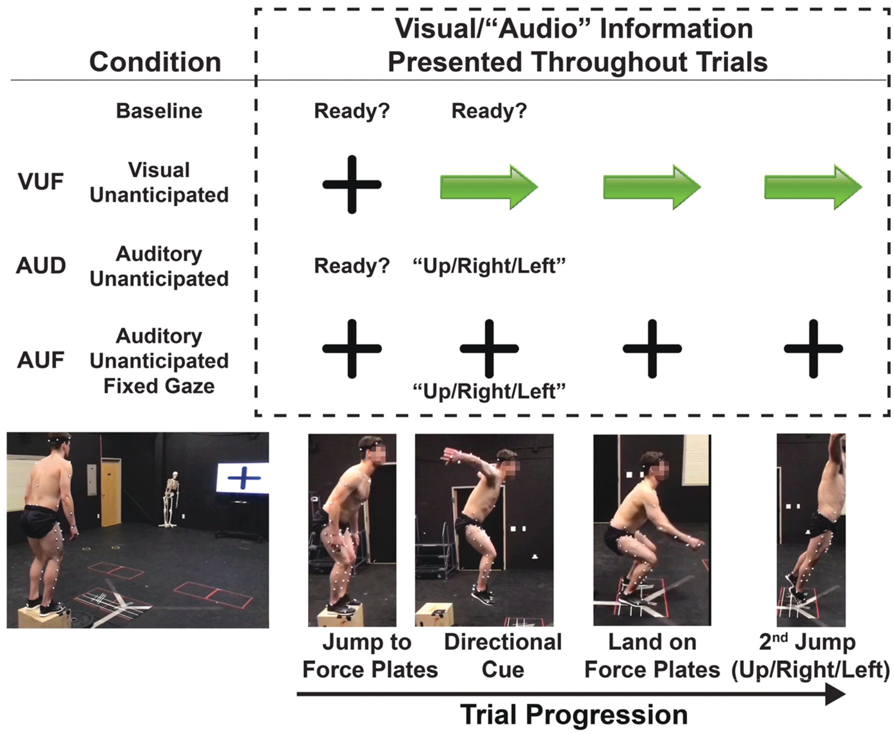

FIGURE 2—Overview of jump–land–jump conditions. Directional cues provided for VUF displayed secondary jump direction via an arrow ~250 ms before initial contact from the first landing. AUD and AUF indicated secondary jump direction via auditory cue that initiated ~350 ms before initial contact from the first jump, with the audio files being ~100 ms in duration. AUF required participants to fixate on a cross in front of them throughout the trial. The second jump was in one of three directions: straight up, 45° to the left and 1 m forward, or 45° to the right and 1 m forward. Analysis for this study focused on trials with a straight-up second jump direction.

plug-in gait markerset was used for the upper body, with markers on the iliac crests used to assist pelvis tracking during the jumping tasks. Marker and force plate data were low-pass filtered using a 15-Hz fourth-order Butterworth filter in Visual3D (HAS-Motion, Kingston, Ontario, Canada). A CODA pelvis definition was used and hip joint centers estimated the Visual3D implementation of Bell et al. prediction equations (55). Knee and ankle joint centers were defined as the midpoints of markers on the femoral epicondyles and malleoli, respectively. Lower extremity segments were defined with the z axis oriented from distal toward proximal joint centers, y axis oriented anteriorly, and x axis oriented to participants' right. An inverse kinematics model was used with lower extremity degrees of freedom constrained to 3 rotational degrees of freedom at the hip and knee and 2 rotational degrees of freedom at the ankle. The Quasi-Newton solver in Visual3D was used to obtain pose estimates for the lower extremities throughout the jumping tasks. A cardan x–y–z rotation sequence was used to calculate joint angles. Initial contact was defined for each limb as the frame where the vertical ground reaction force first exceeded 10 N during the initial landing.

The primary dependent variables for this study were based on biomechanical variables previously reported to predict second ACL injuries (56). These variables consisted of 1) impulse of the internal/external rotation moment for the uninvolved/uninjured hip during the first 10% of stance phase following initial contact, 2) asymmetry in the knee extensor moments when limbs first made initial contact, and 3) the range in knee abduction angle of the ACLR limb from initial contact to the minimum vertical position of the center of gravity. Paterno et al. (56) reported that less external rotator moments at the uninvolved hip, increased knee extensor moment asymmetry at initial contact (relatively more extensor moment at the uninvolved/uninjured knee), and increased frontal plane knee motion were related to increased risk of sustaining a second ACL injury and were therefore interpreted as “risky” biomechanics in our study. To test our hypothesis, DTC (unanticipated − anticipated) for the uninvolved hip impulse (DTC_Uni-HRot_Imp), asymmetry in knee extensor moment at initial contact (DTC_KEM_Asym), and knee abduction angle range variables (DTC_KAbA_Range) were calculated to characterize the relative deficits introduced by added cognitive challenge of rapid decision making. For consistency in interpretation, we used a convention where positive values indicate a relative increase in perceived risk during the unanticipated conditions for all biomechanical variables (i.e., more internal rotator moment impulse, more knee extensor moment asymmetry, increased knee abduction range).

Power analysis. A sample size of 25 was determined in order to provide 80% statistical power to detect bivariate relationships with magnitudes of $r = 0.6$ with an adjusted significance level of $\alpha = 0.05/3 = 0.0167$ to account for three biomechanical variables of interest (G*Power version 3.1, (57)). The expected effect size was supported by our prior work that identified correlations between balance control strategy and PROMs of at least this magnitude (rho = 0.8) (58). Although these data were from a different motor task (i.e., standing balance), they were used to support the premise that our sample size would be able to detect the relationships between PROMs and physical function in the proposed study.

Statistical analysis. Statistical analysis was performed using R (version 4.4.0) via RStudio (version 2024.04.2 + 764, Posit Software, PBC). Multiple regression models tested for relationships between DTC-dependent variables (i.e., DTC_Uni-HRot_Imp, DTC_KEM_Asym, and DTC_KAbA_Range) and predictor variables of PROMs (ACL-RSI and FJS-12) and "Condition" (baseline, VUF, AUD, and AUF). Models were repeated with the addition of covariates (i.e., age, sex, mass, and time since ACLR surgery) to assess the sensitivity of the relationships to controlling for clinically relevant variables. Q–Q plots of standardized residuals of the models were checked to ensure approximately normal distribution. Significance was set at $\alpha = 0.0167$ to control for the comparison being made for three dependent variables (0.05/3).

Follow-up analyses were performed to support interpretation of the relationships. First, multiple regression models were performed between baseline and DTC estimates, with Condition included again to account for the three unanticipated conditions. Second, we repeated the analyses with dependent biomechanical variables from baseline or dual-task conditions in isolation to evaluate whether the relationships with PROMs differed when considering biomechanics defined by DTC (i.e., primary analysis) versus isolated baseline or dual-task conditions. Third, to explore the potential overlapping variance in DTC explained by PROMs versus baseline biomechanics, we performed follow-up regression models that added factors of baseline biomechanics in isolation and interacting with PROM to the model used for the primary analysis.

RESULTS

Out of the 108 DTC averages (i.e., 36 participant × 3 conditions), one VUF average was excluded due to a data collection issue. Timing of the directional cues for the included data was confirmed in a *post-hoc* test (Supplemental Table 1, Supplemental Digital Content, http://links.lww.com/MSS/D134).

Significant relationships between PROMs and DTC in biomechanical variables were observed for DTC_Uni-HRot_Imp (R^2_{adj} = 19%, $P < 0.001$) (Fig. 3), were trending toward the multiple correction-controlled significance level for DTC_KAbA_Range (R^2_{adj} = 7%, $P = 0.021$), and were not significant for DTC_KEM_Asym ($P = 0.6$) (Table 2). For DTC_Uni-HRot_Imp, higher ACL-RSI scores were associated with relatively less uninvolved hip external rotator moments during the unanticipated conditions (ACL-RSI: $\beta_{std} = 1.6 \times 10^{-3}$ (N·m-s)·kg^{-1}, $P < 0.001$). The trending regression model for DTC_KAbA_Range suggested that higher FJS-12 scores (i.e., less thought toward their knee) were related with relatively greater increases in knee abduction ranges during unanticipated conditions compared with the baseline condition (FJS-12: $\beta_{std} = 0.83°$, $P = 0.002$). The predictor "Condition" was not significant for any model. The addition of covariates into the models did not appreciably influence the statistically significant and trending relationships (Supplemental Table 2, Supplemental Digital Content, http://links.lww.com/MSS/D134).

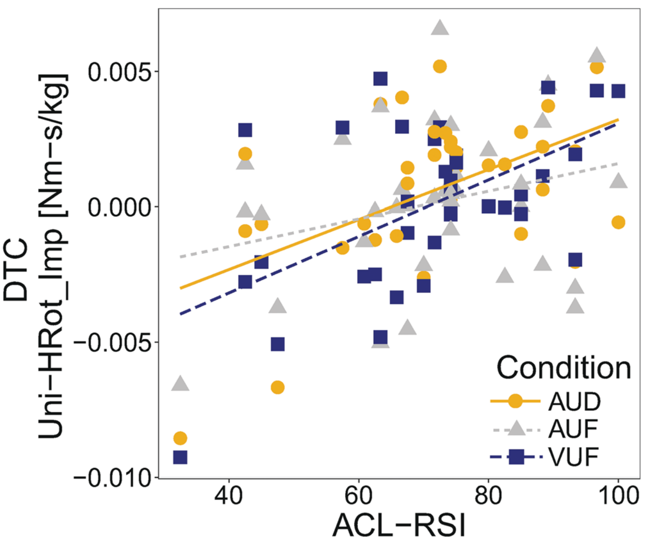

FIGURE 3—Relationship between ACL-RSI and DTC_Uni-HRot_Imp. Higher ACL-RSI scores were associated with less uninvolved hip external rotator moments during the unanticipated conditions.

The first follow-up analysis yielded significant negative relationships between baseline and DTC biomechanical variables for DTC_Uni-HRot_Imp ($\beta_{std} = -0.7 \times 10^{-3}$ (N·m-s)·kg^{-1}, $P = 0.007$) and DTC_KEM_Asym ($\beta_{std} = -2.7 \times 10^{-1}$ %BW-HT, $P < 0.001$), where participants who had less risky baseline biomechanics demonstrated greater DTC. No relationship was observed for DTC_KAbA_Range ($P = 0.5$).

The second follow-up analysis (Supplemental Table 3, Supplemental Digital Content, http://links.lww.com/MSS/D134) indicated that relationships between biomechanical predictors of second ACL injury and PROMs were negligible when considering the biomechanics of the baseline condition in isolation (all coefficient P values >0.05). Significant relationships when considering biomechanics from the dual-task condition in isolation were limited to ACL-RSI with Uni-HRot_Imp ($\beta_{std} = 1.4 \times 10^{-3}$ (N·m-s)·kg^{-1}, $P = 0.004$).

The follow-up investigation into the potential interacting nature of PROMs and baseline biomechanics for explaining variance in DTC for the biomechanical variables indicated maintained relationships for the combined models as compared with considering DTC-PROM and DTC-baseline biomechanics relationships separately (Supplemental Tables 4 and 5, Supplemental Digital Content, http://links.lww.com/MSS/D134). Specifically, when baseline biomechanics and PROMs were included in the same regression models, baseline biomechanics were still negatively associated with DTC_Uni-HRot_Imp ($\beta_{std} = -0.9 \times 10^{-3}$ (N·m-s)·kg^{-1}, $P < 0.001$) and DTC_KEM_Asym ($\beta_{std} = -2.8 \times 10^{-1}$ %

TABLE 2. Outcomes of regression analyses between PROMs and DTC in biomechanics.

DTC	β_{std} ACL-RSI	β_{std} FJS-12	Model Summary
Uni-HRot_Imp, $(N{\cdot}m{\cdot}s){\cdot}kg^{-1}$	**1.6×10^{-3} ($P < 0.001$)**	-0.5×10^{-3} ($P = 0.12$)	**$R^2_{adj} = 19\%$ ($P < 0.001$)**
KEM_Asym, %BW-HT	4.8×10^{-2} ($P = 0.54$)	-1.2×10^{-1} ($P = 0.12$)	$R^2_{adj} = 0\%$ ($P = 0.6$)
Inv-KAbA_Range, °	−0.49 ($P = 0.055$)	**0.83 ($P = 0.001$)**	$R^2_{adj} = 7\%$ ($P = 0.021$)

Bolded values indicate those that reached statistical significance ($P < 0.0167$).
Standardized coefficients with P values are presented for each PROM.
Uni-HRot_Imp, $(N{\cdot}m{\cdot}s){\cdot}kg^{-1}$: impulse of the internal/external rotation moment for the uninvolved hip during the first 10% of stance phase following initial contact. Impulse values are divided by body mass.
KEM_Asym, %BW-HT: Asymmetry in the knee extensor moments when limbs first made initial contact reported as percent of bodyweight (BW) and height (HT).
Inv-KAbA_Range, °: range in knee abduction angle of the ACLR limb from initial contact to the minimum vertical position of the center of gravity reported in units of degrees.

BW-HT, $P < 0.001$), ACL-RSI were significantly associated with DTC_Uni-HRot_Imp ($\beta_{std} = 1.3 \times 10^{-3}$ $(N{\cdot}m{\cdot}s){\cdot}kg^{-1}$, $P < 0.001$), and FJS-12 scores were associated with DTC_KAbA_Range ($\beta_{std} = 0.72°$, $P = 0.002$). R^2_{adj} values were greater in the combined models compared with the PROM-only model for the kinetic dependent variables (Uni-HRot_Imp: 19% ➔ 25%; KEM_Asym: 0% ➔ 14%), but nearly unchanged for Inv-KAbA_Range (R^2_{adj} 7% ➔ 8%). The regression coefficients did not appreciably change when predictors (PROMs or baseline biomechanics) were considered in separate models versus the combined model, which was interpreted as these factors being largely independent of each other regarding their ability to explain variance in DTC outcomes.

DISCUSSION

The purpose of this study was to investigate the clinical utility of cognitive–motor interference by determining the relationship between PROMs and biomechanical predictors of second ACL injuries during jump landings that involved rapid decision making. Significant relationships between PROMs and cognitive–motor interference were identified, but in the opposite direction than originally hypothesized. Specially, worse psychological readiness (ACL-RSI) and greater attention toward the knee (FJS-12) were related to less DTC in biomechanical predictors of second ACL injuries. Importantly, participants who demonstrated less risky biomechanics during the single-task baseline condition demonstrated more DTC. The collective results are consistent with higher functioning participants (better PROMs) who also demonstrate desirable biomechanics during single-task conditions being prone to demonstrating the greatest increases in high-risk biomechanics during the unanticipated scenarios (Supplemental Tables 4 and 5, Supplemental Digital Content, http://links.lww.com/MSS/D134). In contrast, lower functioning participants (worse PROMs) maintained similarly risky biomechanics regardless of additional challenge (less DTC). These findings motivate the complementary insight that cognitive–motor testing can provide when evaluating ACLR patients for their readiness to return to sport and highlight the need for additional work to fully understand the value of cognitive–motor testing in enhancing return to sport determination.

The larger cognitive–motor interference in high performers (i.e., high PROM scores and less risky single-task biomechanics) can be interpreted through the lens of cognitive–motor reserve and also highlights a potential opportunity to augment RTS assessment. The framework of cognitive–motor reserve suggests that impaired performance arises as the amount of reserve resources become limited, with dual-task scenarios depleting more resources (59). ACLR patients with poor PROM scores and/or who have not regained strength or neuromuscular control in common single-task RTS assessment settings (e.g., triple hop, isokinetic strength) already indicate insufficient cognitive–motor reserve. Additional cognitive challenge (e.g., visual–cognitive reactive triple hop (29)) may then result in less DTC because the patient is already near a performance floor. In contrast, ACLR patients with strong psychological readiness and who perform well on single-task movement assessments (i.e., a patient who would meet standard RTS) may still have insufficient reserve to accommodate the added demands of dual-task scenarios, resulting in these individuals having the potential to demonstrate the greatest dual-task impairment and therefore the most to benefit from added cognitive–motor assessments. A subset of these patients may adopt a more cognitively demanding compensatory strategy, which is prone to larger dual-task detriments when challenging cognitive–motor demands are introduced. The dual-task deficits may indicate that robust neuromuscular control has not yet been attained by the patient and that they may demonstrate more risky movement patterns during sport than is indicated by standard RTS assessments. Collectively, layering a cognitive–motor assessment level to RTS decision making following patients' ability to meet standard single-task criteria would provide an opportunity to identify patients with poor cognitive–motor function that is masked during single-task assessment alone, and potentially serve as an additional tool to mitigate the persistent high risk of sustaining a second ACL injury. A number of dual-task clinical tests have been developed, and others have already advocated for the use of cognitive–motor assessments in rehabilitation and RTS assessment (6,9,11,28,29,59). The results from our study provide novel evidence to support the potential clinical utility of cognitive–motor assessments for otherwise high-performing individuals. Further research is needed to demonstrate the extent that dual-task assessment adds to second injury prediction, optimize the tests and outcomes of these tests, and determine clinically meaningful thresholds for their outcomes to support impactful clinical translation.

Our finding of larger cognitive–motor interference in individuals with higher PROM scores also provides new perspective to understanding prior reports of high confidence being related to increased risk of a second ACL injury (32,34,42,60). In addition to the patient-specific characteristics that may drive

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some patients to be less risk averse and more ambitious to return to sport environments, our results provide a biomechanical perspective to potentially identify overly confident ACLR patients. Specifically, despite high ACL-RSI scores, some participants demonstrated larger cognitive–motor interference. This indicates that, although their confidence may have aligned with single-task biomechanics, it was misleading in terms of indicating participants' ability to mitigate biomechanical impairments when additional cognitive challenges were introduced during a dynamic movement. Future research is needed to determine if a combination of low DTC alongside low-risk baseline biomechanics and high PROM scores provides a more rigorous and clinically meaningful rehabilitation target to mitigate risk of subsequent injury. This scenario further highlights the added perspective that cognitive–motor assessment can provide to more comprehensively identify patient-specific behavior that could be masked if only considering single-task biomechanical assessments and PROMs.

This study augments prior research into relationships between PROMs and lower extremity biomechanics by focusing on cognitive–motor interference and using biomechanical predictors of second ACL injury as primary outcome variables. Prior research has focused on single-task conditions, which yielded multiple reports of higher kinesiophobia associating with risky lower extremity biomechanics (i.e., stiffer landing, increased knee abduction angle) during jumping tasks (35–37). These relationships have been interpreted using a stress and injury theoretical framework, where prior injury could elicit a more attentionally demanding approach to a perceived risky task (e.g., landing from a jump) (35,61). This interpretation is consistent with ACLR individuals increasing reliance on visual–cognitive resources to potentially mitigate performance deficits. This visual–cognitive compensatory strategy is ineffective when additional cognitive challenges are introduced (e.g., cognitive–motor scenarios). Therefore, the visual–cognitive compensatory strategy may mask performance deficits in single-task scenarios that become more discernable during dual-task assessments, which is consistent with prior work (50,58). As a supplemental analysis for our current dataset, we found that repeating the regression analyses on baseline and unanticipated conditions separately, rather than the difference score, indicated stronger PROM–biomechanics relationships for the unanticipated conditions than baseline biomechanics, which had no significant relationships (Supplemental Table 3, Supplemental Digital Content, http://links.lww.com/MSS/D134). These results give an example of how single-task biomechanics may mask altered movement strategies (e.g., increased visual–cognitive approach) for ACLR, and support the complementary perspective that cognitive–motor assessments provide in more completely understanding relationships between PROMs and injury-relevant biomechanics following ACLR.

Although our data and prior work support the potential clinical value for cognitive–motor RTS assessments, optimal choices for what cognitive–motor tests to use and the most valuable outcome metrics remain unknown. Increased visual and multisensory processing associated brain activity in ACLR individuals provides rationale for cognitive–motor RTS tasks to emphasize visual–cognitive challenges to probe potential compensatory strategies that use visual–cognitive resources to mask performance deficits in single-task conditions. A number of reliable, clinically feasible tests with visual–cognitive demands have been developed in the context of ACLR RTS (28,29,62); however, the set of these and/or other tests that best capture cognitive–motor function to augment efforts to reduce second ACL injury risk remains an important area for continued research. It also remains unknown whether cognitive–motor function is better or complementarily captured by difference scores (i.e., difference between dual-task condition and a single-task baseline performance) or performance on cognitive–motor tests alone (e.g., hop distance on visual-reactive triple hop). Our current dataset yielded similar findings when dependent variables were defined by difference score (DTC, Table 2) versus cognitive–motor outcome (dual-task, Supplemental Table 3, Supplemental Digital Content, http://links.lww.com/MSS/D134), with DTC associations having increased strength and significance of relationships. Notably, the different methods for defining dependent variables provide somewhat complementary perspectives on cognitive–motor function, with the difference score adjusting for individuals' baseline performance and more isolating cognitive–motor *interference*. Because of strong correlations between single- and dual-task performance, difference scores can suffer from loss in reliability (63), raising questions for difference scores as a robust clinical outcome. Collectively, additional research is needed to understand the optimal set of cognitive–motor assessments and outcome metrics to support their effective inclusion into clinical-decision making for RTS.

Several limitations are important to keep in mind when interpreting the findings of this study. First, prospective studies that investigate the relationship between cognitive–motor function and actual second ACL injury risk would provide stronger evidence for their clinical relevance. However, basing our analysis on biomechanical variables previously reported to predict second ACL injury risk (56) and the use of PROMs provides an initial effort to determine clinical relevance in the confines of a cross-sectional study design, which can serve as support for necessary future longitudinal studies. Furthermore, pre-injury cognitive–motor function is not known for the current cross-sectional study cohort, limiting the ability to determine if poor cognitive–motor function preceded ACL injury and rehabilitation and/or was influenced by these events. In addition, participants in our study were treated by different clinics in which varied rehabilitation programs and RTS assessments may have been implemented. The extent that different clinics integrated cognitive–motor training into rehabilitation is not known and could enable more precise estimates of the relationships of interest. However, not restricting participants to a single rehabilitation program enables the study findings to reflect relationships that may generalize across clinics. Our sample population was 72% female and most commonly participating in downhill skiing among other sports. The extent that the relationships generalize to other demographic and sport characteristics needs to be determined through additional research. Notably, the high percentage of female participants aligns more closely with demographics in Zarzycki et al. (32), who found increased risk with better PROM scores. Finally, although several significant relationships were observed, the adjusted R^2 values were fairly low and suggest that considerable variance is explained by other sources. Despite these limitations, this study provides supporting evidence for the unique and complementary perspective on ACLR patient function that can be gained through cognitive–motor assessment.

CONCLUSIONS

ACLR patients with desirable single-task jump landing biomechanics and high PROM scores demonstrated the greatest shifts toward higher injury risk mechanics when an additional unanticipated cognitive challenge was added to the jumping task. These findings may indicate the value of including cognitive–motor challenges in ACLR RTS assessments, which are currently absent in common RTS criteria.

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