Journal of Athletic Training 2024;59(7):751–761
doi: 10.4085/1062-6050-0259.23

www.natajournals.org

Trunk and Lower Extremity Biomechanics in Female Athletes With and Without a Concussion History

Eric J. Shumski, MS*; Jeonghoon Oh, PhD†; Julianne D. Schmidt, PhD, LAT, ATC*; Robert C. Lynall, PhD, ATC*

*UGA Biomechanics Laboratory, University of Georgia, Athens; †Center of Neuroregeneration, Houston Methodist Research Institute, TX

Context: Athletes with a history of concussion are at a greater risk for lower extremity musculoskeletal injury. Female athletes may be at an even greater risk than male athletes. Previous researchers on postconcussion landing biomechanics have focused on the lower extremities, but the trunk plays a crucial role as an injury risk factor.

Objective: To compare lower extremity and trunk biomechanics during jump-landing and cutting maneuvers between female athletes with and those without a concussion history.

Design: Cross-sectional study.

Setting: Biomechanics laboratory.

Patients or Other Participants: A total of 26 athletes (mean ± SD age = 19.0 ± 1.3 years, height = 1.68 ± 0.07 m, mass = 64.02 ± 6.76 kg, body mass index = 22.58 ± 1.97 kg/m^2; median [interquartile range] time since most recent concussion = 37.5 months [25.0 months, 65.8 months]) with a concussion history and 38 athletes (age = 19.0 ± 1.1 years, height = 1.71 ± 0.08 m, mass = 64.72 ± 9.45 kg, body mass index = 22.14 ± 1.80 kg/m^2) without a concussion history.

Main Outcome Measure(s): Peak kinetics (vertical ground reaction force, vertical loading rate, external knee-abduction moment, and external knee-flexion moment) and kinematics (trunk-flexion angle, trunk lateral-bending angle, ankle-dorsiflexion angle, knee-flexion angle, knee-abduction angle, and hip-flexion angle) were obtained during the eccentric portion of jump-landing and cutting tasks. Separate 2 (group) × 2 (limb) between- and within-factors analyses of covariance were used to compare outcomes between groups. We covaried for time since the most recent concussion and the limb that had a history of musculoskeletal injury.

Results: Athletes with a concussion history displayed a greater peak knee-abduction angle in their nondominant limb than their dominant limb ($P = .01$, $\eta_p^2 = 0.107$) and the nondominant limb of athletes without a concussion history ($P = .02$, $\eta_p^2 = 0.083$) during jump landing. They also had less trunk lateral bending during cutting compared with athletes without a concussion history ($P = .005$, $\eta_p^2 = 0.126$).

Conclusions: Our results indicated landing biomechanics are different between female athletes with and those without a concussion history. This finding may be due to impairments in neuromuscular control postconcussion that may ultimately increase the risk of subsequent lower extremity injury, although further research is warranted given the cross-sectional nature of our study.

Key Words: mild traumatic brain injury, sports medicine, jump landing, cut, drop landing

Key Points

- Athletes with a concussion history displayed greater knee-abduction angle in their nondominant than dominant limb during jump landing.
- The knee-abduction angle in the nondominant limb was greater in athletes with than those without a concussion history during a jump landing.
- Athletes with a concussion history displayed less trunk lateral bending toward the planted limb during cutting compared with athletes without a concussion history.

In collegiate athletics, concussions account for 6.2% of all reported injuries.[1] Female athletes experience higher concussion rates compared with male athletes in sex-comparable sports.[2] For example, collegiate women's soccer and basketball have a 56% and 61% higher concussion rate, respectively, than men's soccer and basketball.[2] Concussions also cause a myriad of symptoms, such as a slower reaction time, headaches, neck pain, and difficulty concentrating.[3] Female athletes experience these symptoms with greater severity and for a longer time compared with male athletes.[4]

Beyond symptom-based concussion concerns, researchers recently have found a 2 to 4 times greater risk for lower extremity musculoskeletal injury (MSKI) postconcussion.[5] The increased risk for MSKI postconcussion has been found across sport levels and different populations, such as military personnel.[5] Female athletes may also be more likely to sustain a lower extremity MSKI postconcussion than male athletes.[6] For instance, female athletes with a concussion history had 1.88 to 2.54 greater odds of sustaining an ankle sprain or knee injury compared with female athletes without a concussion history; this increased risk was not present among male athletes.[6] Impaired neuromuscular control has been hypothesized to be a potential reason for this increased risk in MSKI.[7] Concussions may lead to altered neuromuscular control through changes in motor planning, cortical excitability, dual-task capabilities, and muscle activation.[7,8] For example, cortical excitability, as measured with transcranial magnetic stimulation, of the brain region controlling the gluteus maximus is related to hip-extensor moment and hip-flexion angle during a single-legged landing.[9] Neuromuscular control can be assessed through dynamic tasks such as jump landing and cutting, which are predictive of MSKI risk independent of concussion history.[10] In addition, some researchers have explored landing and cutting mechanics postconcussion, but specific focus on female athletes is lacking.[11,12]

Most researchers studying postconcussion 3-dimensional landing and cutting have focused on lower extremity joints such as the ankle, knee, and hip.[11–13] For instance, Dubose et al reported that collegiate football players displayed increased hip and decreased knee stiffness approximately 50 days postconcussion compared with preseason stiffness values during a single-legged landing.[11] Avedesian et al reported that adolescent athletes with a concussion history displayed less ankle dorsiflexion during 30- and 60-cm jump-landing tasks compared with those without a concussion history.[13] In addition, although not statistically different, recreationally active individuals with a concussion history have displayed moderate effect sizes for greater vertical ground reaction force (Cohen $d = 0.41$) and vertical loading rate (Cohen $d = 0.46$) compared with those without a concussion history during a drop landing.[14] However, of all the studies in which 3-dimensional biomechanics postconcussion were examined, only 1 study included trunk as an outcome. Specifically, Lynall et al reported that, at a median of 126 days (range, 28–432 days) postconcussion, individuals displayed greater trunk flexion during an anticipated cut on the nondominant limb compared with matched controls without concussion.[12] Trunk biomechanics have been implicated in numerous injuries, such as anterior cruciate ligament tear.[15] A more thorough understanding of trunk biomechanics postconcussion is warranted, especially among women, who display worse trunk biomechanics compared with men.[16]

Asymmetry between limbs is also related to MSKI risk in populations without concussion.[17] A concussion may differentially influence dominant and nondominant limbs and lead to asymmetric whole-body movements. Lynall et al reported that individuals approximately 126 days postconcussion displayed a longer time to stabilization for their nondominant limb compared with controls.[18] In addition, Wilkerson et al reported that side-to-side asymmetry values during acceleration and reaction-time tasks strongly discriminated between athletes an average of 4.6 years postconcussion and athletes without a concussion history.[19] Therefore, including dominant and nondominant limbs in our analysis may elucidate important differences between groups and limbs.

The purpose of our study was to compare the kinematics and kinetics of the lower extremity and the trunk during jump-landing and cutting tasks between female collegiate athletes with and those without a concussion history. We hypothesized that female athletes with a concussion history would display greater vertical ground reaction force, greater vertical loading rates, smaller ankle-dorsiflexion angles, smaller knee-flexion angles, larger knee-abduction angles, a larger external knee-abduction moment, a larger external knee-flexion moment, smaller hip-flexion angles, smaller trunk-flexion angles, and greater trunk lateral bending compared with athletes without a concussion history. We expected to see these differences across all tasks based on previous literature comparing individuals with and those without a concussion history, previous literature comparing individuals preconcussion and postconcussion, and the fact that female athletes tend to have higher risk biomechanics than male athletes.[11–13,20–25]

METHODS

This study is part of an ongoing clinical research program in conjunction with athletics to biomechanically screen incoming student-athletes before they began their collegiate athletic careers. All participants provided written informed consent, and the study protocol was approved by the Institutional Review Board of the University of Georgia (PROJECT00000876).

Participants

Given that some of our data (concussion history, demographics) came from the Concussion Assessment, Research and Education Consortium of the National Collegiate Athletic Association and US Department of Defense, athletes had to consent both to the clinical research project study and the Concussion Assessment, Research and Education Consortium to be included. Athletes were included if they were varsity level and medically cleared for competition. We did not exclude athletes based on injury history or orthopaedic surgery history, as is common in stricter biomechanics research.[20] The only exclusion criterion was not consenting to participate in the research. Two participants reported a concussion history but no date (month or year) and were removed from all analyses. The final sample (n = 64) included 26 athletes with and 38 athletes without a concussion history.

Concussion history was self-reported and collected using the Michigan TBI History form.[26] Athletes self-reported concussion history as diagnosed or undiagnosed. Three participants only reported the year of their most recent concussion. The month of June was used for analyses of these participants. Injury and orthopaedic surgery histories were also self-reported by athletes. *Injury* was defined as a traumatic injury to a ligament, such as a tear, meniscus damage, or fracture to the lower extremity. Minor injuries such as sprains, in which athletes immediately returned to activity, and upper extremity injuries were not considered in the analysis. *Surgery* was defined as any kind of surgery to the lower extremity. *Dominant limb* was defined as the preferred limb for kicking a soccer ball for distance.

Jump-Landing and Cutting Instructions

A 30-cm-high box was placed a distance half the athletes' height away from 2 force plates (Bertec). Athletes were instructed to stand on the box and get into an athletic position (ie, knees and hips slightly flexed) when the researcher (E.S. or J.O.) said, “Get set.” A green light was illuminated randomly by a member of the research team (E.S. or J.O.) within 5 seconds of athletes assuming the “get set” position.[27] The illumination of the light was the cue for the athletes to jump forward, not up, toward the 2 force plates. Athletes were instructed to react as quickly as possible to the light. For the jump-landing task, they were required to land with both feet simultaneously and fully on the 2 force plates (1 foot per plate) and, immediately on landing, to jump straight up as high as possible. For the cutting task, athletes were required to land on 1 limb, immediately and explosively cut to the opposite direction at a 45° angle (eg, left limb landing, right-cut direction), and run through a set of cones. Both tasks were considered unsuccessful and were repeated if participants jumped up for height from the box rather than straight forward, they stepped rather than jumped off the box, or their feet did not land fully on the force plate(s). All athletes were given at least 1 practice trial for each task and could practice until they were comfortable with the task. Three successful jump landings and cuts off both limbs (6 total cuts, 3 in each direction) were collected.

Data Processing and Reduction

Retroreflective markers were placed bilaterally on the acromioclavicular joint, iliac crest, greater trochanter, anterior-superior iliac spine, medial and lateral femoral epicondyles, medial and lateral malleoli, calcaneus, fifth metatarsal, and second metatarsal. A marker was also placed on the sternal notch. A cluster of noncollinear markers was placed on the posterior-superior iliac spine and sacral body and placed bilaterally on the thigh, shank, and foot. Static calibration markers were removed before jumping and cutting. Marker position data were sampled at 240 Hz with an 8-camera (Qualisys MIQUIS; Qualisys Systems) motion capture system. Force plate data were sampled at 1200 Hz.

Raw marker position data and force plate data were exported to Visual 3D (C-Motion Inc) software for analysis. All data were processed with a fourth-order, low-pass Butterworth filter at 10 Hz. The anterior- and posterior-superior iliac spines defined the *pelvis*, hip joint centers were estimated using the method of Bell et al, knee-joint centers were estimated using the midpoint between the medial and lateral femoral epicondyles, and ankle-joint centers were estimated using the midpoint between the medial and lateral malleoli.[28] Euler-Cardan angles (Y-X-Z rotation sequence) were used to calculate the hip, knee, and ankle angles. *Hip motions* were defined as the thigh relative to the pelvis, *knee motions* were defined as the shank relative to the thigh, and *ankle motions* were defined as the foot relative to the shank. *Trunk motion* was defined relative to the global axis system (Y-X-Z rotation). Rotation about the y-, x-, and z-axes was flexion-extension, abduction-adduction (trunk lateral bending), and internal-external rotation, respectively.

For the jump landing, trunk lateral bending was calculated as peak bending toward either limb. In other words, the largest displacement toward (away from straight up-down [0°]) either the dominant or nondominant limb was used in the analysis. During cutting, the largest value toward the cutting limb (ie, planted limb) for peak trunk lateral-bending angle was used in the analysis.

Joint moments were calculated with standard inverse dynamics and resolved in the proximal segment coordinate system. Vertical loading rate was calculated as the first derivative of the vertical ground reaction force slope. Joint moments were normalized to the product of body weight and height (BW $\times$ HT). Vertical ground reaction force and loading rate were normalized to body weight ($\times$BW).

Peak kinetics (vertical ground reaction force, vertical loading rate, external knee-abduction moment, and external knee-flexion moment) and kinematics (ankle-dorsiflexion angle, knee-flexion angle, knee-abduction angle, hip-flexion angle, trunk-flexion angle, and trunk lateral-bending angle) were obtained during the eccentric portion of the task (ie, initial ground contact to peak knee-flexion angle). *Initial ground contact* was defined as the point at which vertical ground reaction force exceeded 10 N. Kinetic and kinematic variables were averaged across all 3 trials for each task. Limbs were analyzed separately rather than averaged together, as previous researchers have shown asymmetries in movement after concussion and different results for each limb compared with controls.[18,19]

Statistical Analysis

Demographic information such as age, height, mass, and body mass index was compared using a series of independent *t* tests. The proportions of lower extremity injuries or surgeries (yes or no), injured or surgical limb (none, both, dominant, or nondominant), limb dominance (left or right), and sport (soccer, gymnastics, or volleyball) were compared between groups (concussion history or no concussion history) using the Fisher exact test (Table 1).

Separate 2 (group) $\times$ 2 (limb) between-within analyses of covariance (ANCOVAs) with Bonferroni adjustments were used to compare jump-landing and cutting biomechanics. The between factors were athletes with and without a concussion history. The within factors were the dominant and nondominant limb. The covariates were mean centered time since the most recent concussion and the limb that had a history of MSKI (coded as *none*, *both*, *dominant*, or *nondominant*).[12] Mean centering was calculated by subtracting each athlete's time since their most recent concussion from the group mean time since their most recent concussion, then assigning the control group a value of 0.[12] Trunk flexion and lateral bending during jump landing were compared using a 1-way ANCOVA as both limbs contacted the ground simultaneously. Partial η^2 (η_p^2) effect sizes were interpreted as *small* ($\leq$0.05), *medium* (0.06–0.13), and *large* ($\geq$0.14) and reported with 90% CIs. We chose a 90% CI because η_p^2 values cannot be $<$0 because *F* tests are 1-sided; therefore, using a 95% CI may include zero when the *P* value is significant, causing confusion.[29–31] Covariate adjusted means with 95% CIs and mean differences with 95% CIs are reported. An α level of .05 was established a priori. We used IBM SPSS Statistics for Windows (version 28.0; IBM Corp) for analyses.

We performed a sensitivity analysis to confirm that the 3 athletes who reported only the year of their concussion were not influencing the results. We removed the 3 athletes, recalculated the mean centered time since their most recent concussion, and rechecked the ANCOVA results. Our sensitivity analysis results were the same as the full analysis results.

RESULTS

None of the demographic data were different between groups (Table 1). Athletes with a concussion history reported the following injuries and surgeries: 1 lateral meniscus tear, 1 Achilles tendon tear, 1 knee arthroscopic surgery, and 3 anterior cruciate ligament tears. Athletes without a concussion history reported the following injuries and surgeries: 1 medial collateral ligament tear, 1 shank fracture, 2 ankle fractures, 6 anterior cruciate ligament tears, 1 meniscus tear, 1 femur fracture, and 2 unspecified ankle surgeries. A Fisher exact test revealed no differences in the proportion of injury or surgery type between groups ($P = .67$). Raw (non–covariate-adjusted),

Table 1. Patient Characteristics[a]

Characteristic	No Concussion History (n = 38)	Concussion History (n = 26)	*P* Value
Age, mean ± SD, y	19.0 ± 1.1	19.0 ± 1.3	.83
Height, mean ± SD, m	1.71 ± 0.08	1.68 ± 0.07	.23
Mass, mean ± SD, kg	64.72 ± 9.45	64.02 ± 6.76	.73
Body mass index, mean ± SD	22.14 ± 1.80	22.58 ± 1.97	.36
Lower extremity injury or surgery, % (No.) yes	36.8 (14)	23.1 (6)	.28
Injured or surgical limb, % (No.)[b]			.74
None	63.2 (24)	76.9 (20)	
Both	2.6 (1)	0.0 (0)	
Dominant	21.1 (8)	15.4 (4)	
Nondominant	13.2 (5)	7.7 (2)	
Right limb dominant, % (No.)	100.0 (38)	84.6 (22)	.02
Sport, % (No.)			.93
Gymnastics	23.7 (9)	23.1 (6)	
Soccer	60.5 (23)	65.4 (17)	
Volleyball	15.8 (6)	11.5 (3)	
Concussion frequency, % (No.)			
0	100.0 (38)	0.0 (0)	
1	NA	53.8 (14)	
2	NA	34.6 (9)	
3+	NA	11.5 (3)	NA
Time since most recent concussion, median (IQR), mo	NA	37.5 (25.0, 65.8)	NA

Abbreviations: IQR, interquartile range; NA, not applicable.
[a] Percentages were rounded, and the sum may not equal 100%.
[b] Any athlete in the "both" category for injured/surgical limb outcome was not reported in duplicate in the "dominant" or "nondominant" category.

time-normalized waveforms are shown in Figures 1 and 2 for all biomechanics outcomes.

Jump Landing

We observed a group-by-limb interaction for peak knee-abduction angle ($F_{1,60} = 4.6$, $P = .04$, $\eta_p^2 = 0.071$ [90% CI = 0.002, 0.185]). The peak knee-abduction angle in the nondominant limb was larger in athletes with than those without a concussion history (mean difference = 4.35°; 95% CI = 0.63°, 8.08°; $P = .02$, $\eta_p^2 = 0.083$ [90% CI = 0.006, 0.201]). Athletes with a concussion history displayed larger peak knee-abduction angles in their nondominant than dominant limb (mean difference = 4.30°; 95% CI = 1.08°, 7.51°; $P = .01$, $\eta_p^2 = 0.107$ [90% CI = 0.014, 0.229]). No other interactions were found (P range = .09–.89; Table 2; Supplemental Table 1, available online at https://dx.doi.org/10.4085/1062-6050-0259.23.S1).

No group main effects were observed for any jump-landing outcomes (P range = .14–.77; Table 2; Supplemental Table 1).

We observed a limb main effect for peak vertical ground reaction force ($F_{1,60} = 4.6$, $P = .041$, $\eta_p^2 = 0.068$ [90% CI = 0.002, 0.185]), peak knee-abduction angle ($F_{1,60} = 4.2$, $P = .046$, $\eta_p^2 = 0.065$ [90% CI = 0.001, 0.177]), and peak external knee-flexion moment ($F_{1,60} = 7.3$, $P = .009$, $\eta_p^2 = 0.108$ [90% CI = 0.015, 0.231]). However, post hoc analysis showed no difference between limbs for peak vertical ground reaction force (mean difference = 0.09 ×BW; 95% CI = −0.01, 0.19 ×BW; $P = .08$, $\eta_p^2 = 0.052$ [90% CI = 0.000, 0.159]). The peak knee-abduction angle (mean difference = 1.75°; 95% CI = 0.16°, 3.34°; $P = .03$, $\eta_p^2 = 0.075$ [90% CI = 0.003, 0.190]) and peak external knee-flexion moment (mean difference = 0.02 BW × HT; 95% CI = 0.01, 0.02 BW × HT; $P < .001$, $\eta_p^2 = 0.382$ [90% CI = 0.215, 0.497]) were greater in the nondominant than the dominant limb. We observed no other limb main effects (P range = .05–.78; Table 2; Supplemental Table 1).

Dominant- and Nondominant-Limb Cut

No group-by-limb interactions were found (P range = .07–.88; Table 3; Supplemental Table 2).

We observed a group main effect for peak trunk lateral-bending angle ($F_{1,60} = 8.7$, $P = .005$, $\eta_p^2 = 0.126$ [90% CI = 0.023, 0.252]). Athletes with a concussion history displayed a smaller peak trunk lateral-bending angle toward the planted limb compared with athletes without a concussion history (mean difference = 4.75°; 95% CI = 1.52°, 7.97°; $P = .005$, $\eta_p^2 = 0.126$ [90% CI = 0.023, 0.252]). No other group main effects were found (P range = .13–.80; Table 3; Supplemental Table 2).

A limb main effect was found for peak external knee-abduction moment ($F_{1,60} = 15.3$, $P < .001$, $\eta_p^2 = 0.206$ [90% CI = 0.067, 0.332]) and peak trunk lateral-bending angle ($F_{1,60} = 7.0$, $P = .01$, $\eta_p^2 = 0.104$ [90% CI = 0.014, 0.226]). Peak trunk lateral bending toward the planted, nondominant limb was greater during cuts with the nondominant than dominant limb (mean difference = 2.24°; 95% CI = 0.97°, 3.532°; $P < .001$; $\eta_p^2 = 0.171$ [90% CI = 0.047, 0.300]). Peak external knee-abduction moment was smaller during cuts with the nondominant than dominant limb (mean difference = 0.006°; 95% CI = 0.004°, 0.008°; $P < .001$; $\eta_p^2 = 0.315$ [90% CI = 0.151, 0.434]). We observed no other limb main effects (P range = .10–.88; Table 3; Supplemental Table 2).

DISCUSSION

Athletes with a concussion history displayed larger nondominant-limb knee-abduction angles during jump landing and less trunk lateral bending during cutting tasks compared

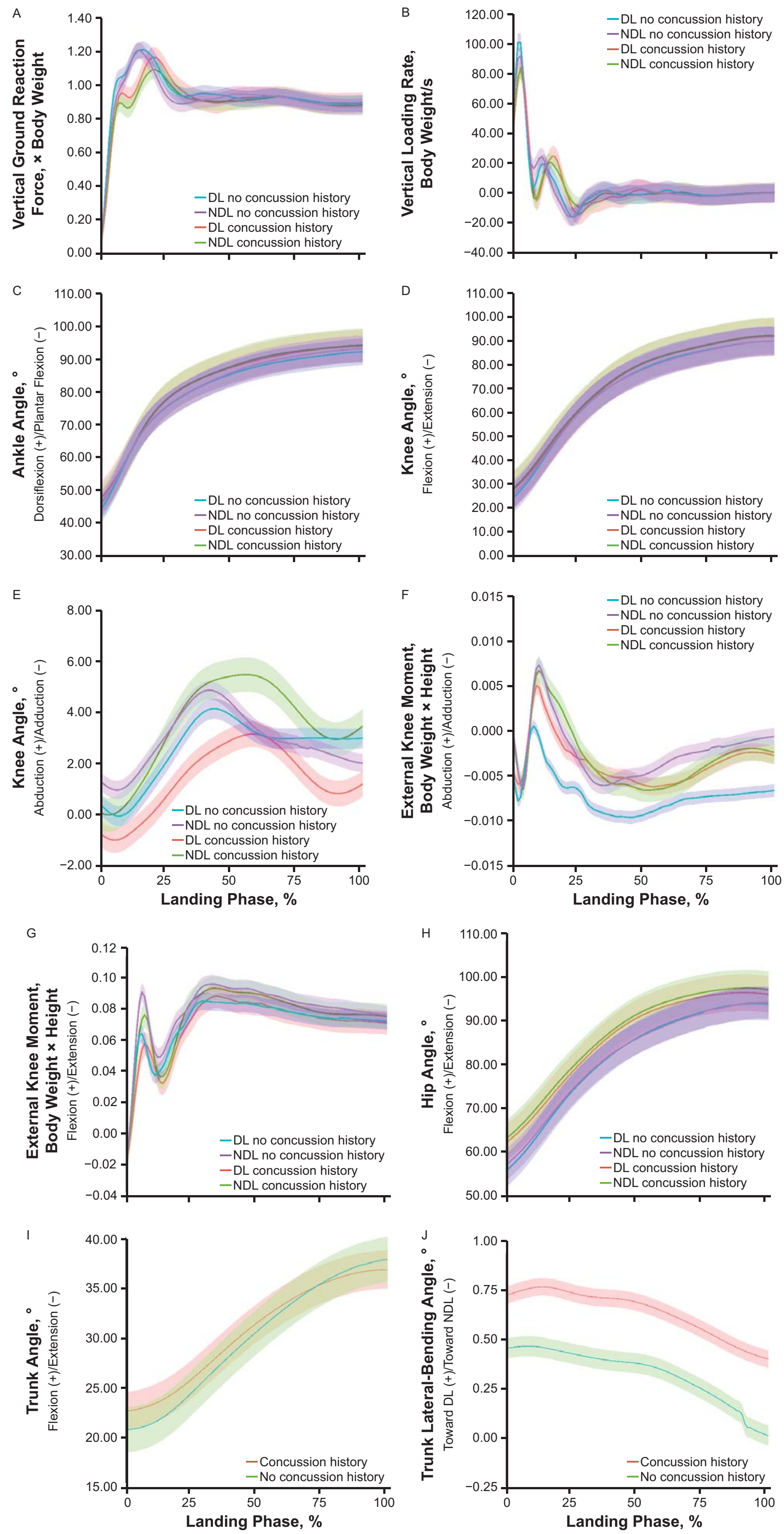

Figure 1. Jump landing. Raw (non–covariate-adjusted), time-normalized landing waveforms. A, Vertical ground reaction force. B, Vertical loading rate. C, Ankle angle. D and E, Knee angle. F and G, External knee moment. H, Hip angle. I, Trunk flexion angle. J, Trunk lateral-bending angle. The landing phase is from initial ground contact (0%) to peak knee-flexion angle (100%). Abbreviations: DL, dominant limb; NDL, nondominant limb.

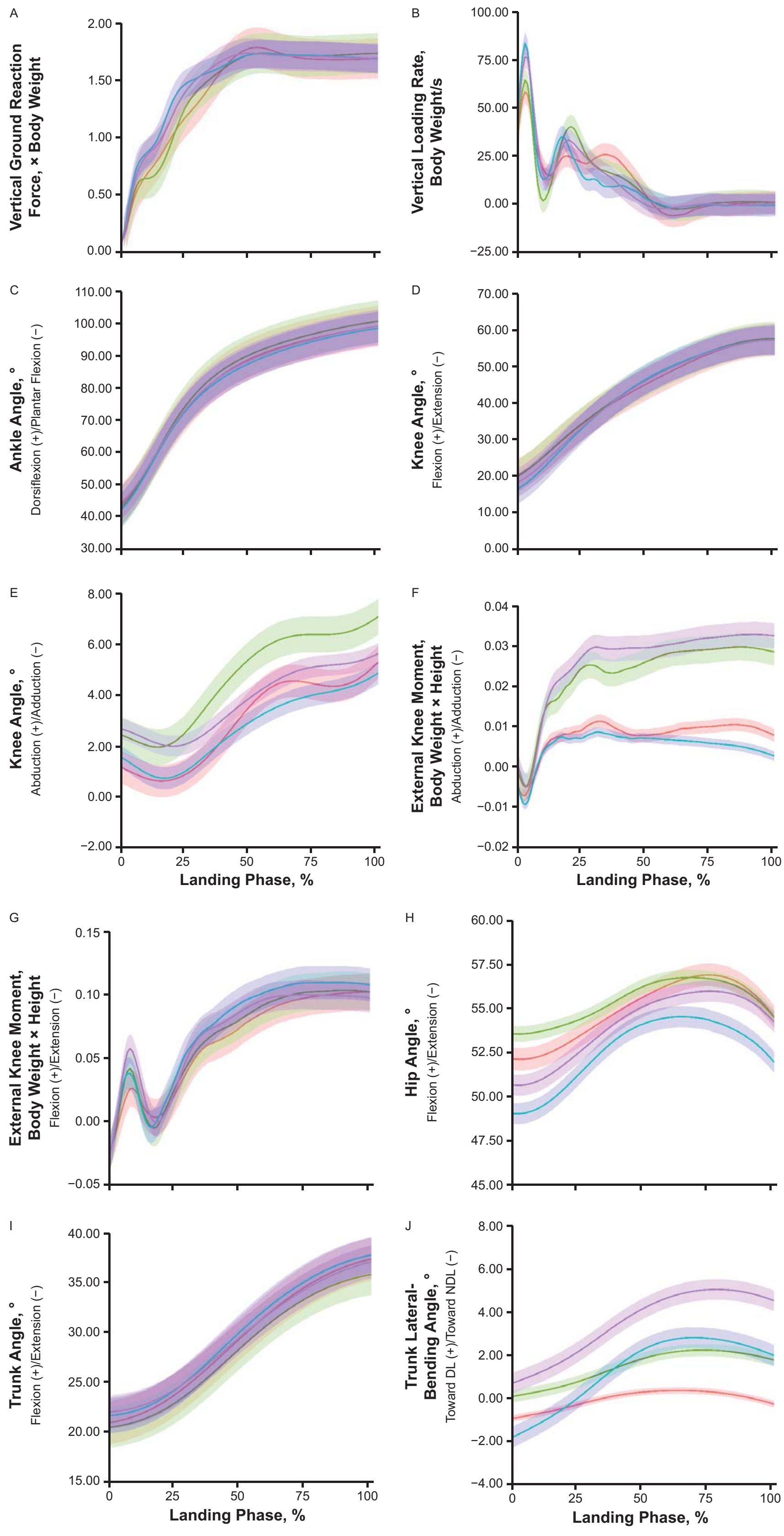

Figure 2. Dominant- and nondominant-limb cuts. Raw (non–covariate-adjusted), time-normalized landing waveforms. A, Vertical ground reaction force. B, Vertical loading rate. C, Ankle angle. D and E, Knee angle. F and G, External knee moment. H, Hip angle. I, Trunk flexion angle. J, Trunk lateral-bending angle. The landing phase is from initial ground contact (0%) to peak knee-flexion angle (100%). Abbreviations: DL, dominant limb; NDL, nondominant limb.

Table 2. **Jump-Landing Outcomes Compared Between Limbs and Groups**

Outcome	Limb	Group, Covariate Adjusted Mean (95% CI)[a]		*P* Value	
		No Concussion History (n = 38)	Concussion History (n = 26)	Group × Limb Interaction	Group Main Effect
Vertical ground reaction force, ×BW[b]	Dominant	1.8 (1.6, 3.0)	1.8 (1.6, 2.0)	.23	.49
	Nondominant	1.8 (1.6, 3.0)	1.6 (1.4, 1.8)		
Vertical loading rate, BW/s	Dominant	126.5 (108.6, 144.3)	118.8 (95.6, 142.1)	.59	.77
	Nondominant	115.5 (99.7, 131.34)	114.3 (93.7, 134.9)		
Ankle-dorsiflexion angle, °	Dominant	92.7 (90.3, 95.0)	93.8 (90.8, 96.9)	.89	.60
	Nondominant	93.3 (91.0, 95.5)	94.1 (91.2, 97.0)		
Knee-flexion angle, °	Dominant	90.2 (84.9, 95.5)	91.4 (84.5, 98.3)	.43	.64
	Nondominant	88.7 (83.1, 94.3)	92.2 (85.0, 99.5)		
Knee-abduction angle, °[b,c]	Dominant	6.9 (5.0, 8.8)	6.2 (3.7, 8.7)	.04	.21
	Nondominant	6.1 (4.2, 8.1)	10.5 (8.0, 13.0)		
External knee-abduction moment, BW × HT	Dominant	0.02 (0.02, 0.03)	0.01 (0.01, 0.02)	.17	.18
	Nondominant	0.02 (0.01, 0.02)	0.02 (0.01, 0.02)		
External knee-flexion moment, BW × HT[b]	Dominant	0.11 (0.10, 0.13)	0.10 (0.09, 0.12)	.09	.14
	Nondominant	0.14 (0.12, 0.15)	0.11 (0.09, 0.13)		
Hip-flexion angle, °	Dominant	93.3 (85.9, 100.8)	100.7 (91.0, 110.4)	.60	.26
	Nondominant	93.2 (86.2, 100.3)	101.5 (92.4, 110.7)		
Trunk-flexion angle, °	NA	36.8 (32.0, 41.6)	40.1 (33.9, 46.4)	NA	.47
Trunk lateral-bending angle, °	NA	2.6 (2.0, 3.2)	3.0 (2.2, 3.7)	NA	.50

Abbreviations: BW, body weight; HT, height; NA, not applicable.
[a] Peak kinetics and kinematics were obtained during the eccentric portion of the task (ie, initial ground contact to peak knee-flexion angle).
[b] Main effect of limb.
[c] Group-by-limb interaction after Bonferroni correction; athletes with a concussion history displayed a larger peak knee-abduction angle in their nondominant limb compared with their dominant limb and the nondominant limb of athletes without a concussion history.

with athletes without a concussion history. Athletes with a concussion history also displayed larger knee-abduction angles during a jump landing with their nondominant than dominant limb. These results were not observed among athletes without a concussion history.

The larger knee-abduction angle during jump landing for athletes with a concussion history may be due to deficits in neuromuscular control. Our results agree with those reported in previous literature, and larger knee-abduction angles are predictive of anterior cruciate ligament tears.[10,21] The causes of larger knee-abduction angle can vary. Researchers have shown that females have larger knee-abduction angles than males during landing, which may be a potential reason for the increased risk of MSKI postconcussion.[6,32] Athletes may have different jump-training–specific backgrounds, which have been shown to decrease the knee-abduction angle during landing.[33] In addition, a large predictor of knee-abduction angle is hip-abductor muscle strength and activation.[34] Neural drive is a large component of muscle strength, and individuals postconcussion have shown lower levels of electromyographic activity compared with controls during hand movements.[35] Individuals have displayed altered cortical measurements of excitability and inhibition for up to 30 years postconcussion.[36,37] Cortical excitability measures also play a key role in muscular strength.[38,39] These factors may have influenced knee-abduction angles in our athletes with a concussion history. Future research on the lower extremity neural control of movement postconcussion, which we did not collect, is warranted.

Although the peak knee-abduction angle throughout stance phase (initial ground contact to toe-off) during a jump-landing task is a risk factor for future anterior cruciate ligament tear, some researchers have reported other findings.[10] For instance, the knee-abduction angle at initial ground contact is a risk factor for anterior cruciate ligament tears.[40] Furthermore, peak knee-abduction moment is also a common risk factor for anterior cruciate ligament tears and other MSKIs but was not different in our study.[10,40,41] In other words, although we found a difference in the knee-abduction angle between individuals with and those without a concussion history, it is not clear if this difference truly means the risk for MSKI is increased. Longitudinal research is needed to explore this connection and should include both peak and initial ground-contact outcomes, as time since concussion has been shown to be related to other landing biomechanics, such as knee-flexion angle.[14]

The reduced trunk lateral bending for athletes with a concussion history was unexpected yet in agreement with findings reported in previous literature.[12] Greater trunk lateral bending toward the planted limb (results from our study) and less trunk flexion are considered dangerous landing positions and risk factors for lower extremity MSKI.[12,15] Lynall et al reported greater trunk flexion among individuals with than those without a concussion history.[12] One possible explanation is that athletes with a concussion history performed the task more quickly (ie, better performance), as researchers have shown better performance metrics are related to more hazardous biomechanics.[42] In addition, Blackburn and Padua focused on group differences between a natural and instructed trunk-flexion position with safer lower extremity biomechanics, but a curvilinear relationship may exist between general trunk control and landing biomechanics that has not been explored.[43] Furthermore, the existence of a previous injury or risk factor (in this case, concussion) may moderate the relationship between what is considered safe or less hazardous. We see this in ankle injuries, for which univariate analyses have indicated ankle-torque asymmetry is not predictive of ankle injuries in a military population; however, the combination of body mass (a known MSKI risk factor) and

Table 3. Cutting Outcomes Compared Between Limbs and Groups

Outcome	Limb	Group, Covariate Adjusted Mean (95% CI)[a] No Concussion History (n = 38)	Concussion History (n = 26)	P Value Group × Limb Interaction	Group Main Effect
Vertical ground reaction force, ×BW	Dominant	2.2 (2.0, 2.4)	2.2 (1.9, 2.5)	.32	.65
	Nondominant	2.2 (2.0, 2.4)	2.1 (1.8, 2.4)		
Vertical loading rate, BW/s	Dominant	109.1 (86.7, 131.5)	85.3 (56.2, 114.5)	.58	.31
	Nondominant	105.7 (84.7, 126.7)	88.6 (61.2, 116.0)		
Ankle-dorsiflexion angle, °	Dominant	98.1 (95.3, 100.9)	100.8 (97.2, 104.4)	.84	.13
	Nondominant	97.6 (94.7, 100.5)	101.1 (97.3, 104.9)		
Knee-flexion angle, °	Dominant	58.0 (54.8, 61.1)	56.2 (52.2, 60.3)	.68	.36
	Nondominant	58.5 (55.4, 61.5)	55.5 (51.5, 59.4)		
Knee-abduction angle, °	Dominant	6.0 (4.0, 7.9)	6.6 (4.1, 9.1)	.32	.26
	Nondominant	6.6 (4.5, 8.7)	9.6 (6.8, 12.3)		
External knee-abduction moment, BW × HT[b]	Dominant	0.02 (0.01, 0.02)	0.01 (0.01, 0.02)	.07	.80
	Nondominant	0.01 (0.01, 0.01)	0.01 (0.01, 0.01)		
External knee-flexion moment, BW × HT	Dominant	0.12 (0.11, 0.14)	0.11 (0.09, 0.13)	.55	.43
	Nondominant	0.12 (0.10, 0.13)	0.11 (0.09, 0.13)		
Hip-flexion angle, °	Dominant	57.1 (53.1, 61.0)	59.7 (54.6, 64.8)	.62	.61
	Nondominant	58.5 (54.3, 62.8)	59.6 (54.1, 65.2)		
Trunk-flexion angle, °	Dominant	36.7 (33.7, 39.7)	38.6 (34.7, 42.5)	.77	.55
	Nondominant	36.0 (33.0, 39.0)	37.2 (33.3, 41.2)		
Trunk lateral-bending angle, °[b,c,d]	Dominant	4.5 (2.3, 6.7)	−0.1 (−3.0, 2.8)	.88	.005
	Nondominant	6.9 (5.3, 8.5)	2.0 (−0.1, 4.1)		

Abbreviations: BW, body weight; HT, height.
[a] Peak kinetics and kinematics were obtained during the eccentric portion of the task (ie, initial ground contact to peak knee-flexion angle).
[b] Main effect of limb.
[c] Main effect of group.
[d] The trunk lateral-bending angle is reported toward (+) or away from (−) the specified limb.

ankle-torque asymmetry in a single model is predictive of MSKI.[44,45] In other words, when several risk factors are explored together, injury prediction improves. Future research should be done to investigate postconcussion trunk neuromuscular control between male and female athletes. Female athletes tend to have greater lateral trunk displacement during various jumping tasks compared with male athletes, as reported in a systematic review of athletes with unknown concussion histories.[46] However, we observed that athletes with a concussion history had less high-risk trunk biomechanics. Trunk biomechanics may not be implicated in future MSKI postconcussion for female athletes; however, longitudinal research is needed for confirmation.

Limb asymmetry is common among healthy individuals.[47] Injuries often lead to more extreme biomechanical asymmetries, and resolving these asymmetries is a common component of rehabilitation programs.[48] Our overall sample, both athletes with and those without a concussion history, may benefit from programs specifically addressing these asymmetries, especially as asymmetries have been related to an increased risk for lower extremity MSKI.[17] However, athletes with a concussion history exhibited larger peak knee-abduction angles during a jump landing in their nondominant than dominant limb, whereas athletes without a concussion history showed no difference. This indicates greater asymmetry in knee-abduction angle for athletes with a concussion history. Lynall et al reported differences between athletes with and those without a concussion history for specific limbs.[18]

In our study, values that were different had medium to large effect sizes. Implementing dynamic movement–focused training programs may be useful for certain individuals during their return-to-play protocols. Jump-training programs have been shown to reduce MSKI in general and reduce fear of movement (kinesiophobia) after anterior cruciate ligament reconstruction.[49,50] Jump training could be important to implement postconcussion because kinesiophobia is associated with an increased risk for MSKI postconcussion.[51] However, no longitudinal evidence supports the widespread adoption of landing-specific training to reduce the risk of lower extremity MSKI postconcussion specifically. Later stages of the concussion return-to-play protocol include dynamic movements and other noncontact sport-specific drills.[52,53] However, the duration and specific exercises in this stage for a given athlete are highly individualized by the medical practitioner treating the athlete. Future research may be done to explore if more time spent in a given stage or step of the return-to-play protocol or specific training protocols reduces MSKI risk postconcussion as jump training reduces MSKI in other populations.[49] Preliminary evidence (Cohen $d = 0.480$) showed that athletes with no MSKI postconcussion spent a longer time in their return-to-play protocols compared with athletes who went on to experience MSKI postconcussion.[54]

Limitations for this study include self-reported concussion and injury history. Although we used self-report measures similar to those used in a previous study, this does not remove the risk of athletes misreporting their histories.[26] In addition, our sample reported a long, heterogeneous time postconcussion, which limits our ability to discuss short- versus long-term landing biomechanics. However, we covaried for time since concussion to help alleviate some of these concerns. Future researchers should focus on these outcomes longitudinally for a comprehensive understanding of movement changes postconcussion. Furthermore, previous injuries are known to influence dynamic movements and neuromuscular control.[48] Although we covaried for previously injured limb(s), this is still a limitation. In addition, our sample did not include male athletes, so we cannot state that female athletes postconcussion demonstrate different landing mechanics than male athletes that may predispose them to a higher risk of MSKI.[6] At the same time, the inclusion of an all-female sample is a strength, as female athletes are highly underrepresented in concussion literature and have a higher risk for lower extremity MSKI.[6,55] Although our sample comprised only female athletes, we did not collect menstrual cycle information. Different menstrual cycle phases alter landing biomechanics and increase the risk for MSKI regardless of concussion history.[56,57]

CONCLUSIONS

Athletes with a concussion history displayed larger knee-abduction angles in the nondominant limb during jump landing and less trunk lateral bending during jump-landing and cutting tasks than athletes without a concussion history. This finding may be due to impairments in neuromuscular control postconcussion, but future research is needed to better understand potential deficits. The reason for less trunk lateral bending among athletes with a concussion history is not entirely clear. A smaller trunk lateral-bending angle toward the planted limb is typically considered a safer landing pattern. Perhaps the existence of a previous risk factor (eg, concussion history) changes what is considered a safe movement pattern. Future longitudinal evidence is needed to explore this concept and the link between landing biomechanics and MSKI postconcussion.

ACKNOWLEDGMENTS

This project was supported, in part, by the Grand Alliance Concussion Assessment, Research and Education Consortium, funded in part by the National Collegiate Athletic Association and the Department of Defense. The US Army Medical Research Acquisition Activity, 820 Chandler Street, Fort Detrick, MD 21702-5014 is the awarding and administering acquisition office. This work was supported by the Office of the Assistant Secretary of Defense for Health Affairs through the Psychological Health and Traumatic Brain Injury Program under Award NO W81XWH-14-2-0151. Opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the Department of Defense (DHP funds).

REFERENCES

1. Zuckerman SL, Kerr ZY, Yengo-Kahn A, Wasserman E, Covassin T, Solomon GS. Epidemiology of sports-related concussion in NCAA athletes from 2009–2010 to 2013–2014: incidence, recurrence, and mechanisms. *Am J Sports Med*. 2015;43(11):2654–2662. doi:10.1177/0363546515599634
2. Chandran A, Boltz AJ, Morris SN, et al. Epidemiology of concussions in National Collegiate Athletic Association (NCAA) sports: 2014/15–2018/19. *Am J Sports Med*. 2022;50(2):526–536. doi:10.1177/03635465211060340
3. McCrory P, Meeuwisse W, Dvořák J, et al. Consensus statement on concussion in sport—the 5th International Conference on Concussion in Sport held in Berlin, October 2016. *Br J Sports Med*. 2017;51(11):838–847. doi:10.1136/bjsports-2017-097699
4. Preiss-Farzanegan SJ, Chapman B, Wong TM, Wu J, Bazarian JJ. The relationship between gender and postconcussion symptoms after sport-related mild traumatic brain injury. *PM R*. 2009;1(3):245–253. doi:10.1016/j.pmrj.2009.01.011
5. Reneker JC, Babl R, Flowers MM. History of concussion and risk of subsequent injury in athletes and service members: a systematic review and meta-analysis. *Musculoskelet Sci Pract*. 2019;42:173–185. doi:10.1016/j.msksp.2019.04.004
6. Houston MN, Hoch JM, Cameron KL, Abt JP, Peck KY, Hoch MC. Sex and number of concussions influence the association between concussion and musculoskeletal injury history in collegiate athletes. *Brain Inj*. 2018;32(11):1353–1358. doi:10.1080/02699052.2018.1512718
7. 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. doi:10.1007/s40279-018-0871-y
8. Chmielewski TL, Tatman J, Suzuki S, et al. Impaired motor control after sport-related concussion could increase risk for musculoskeletal injury: implications for clinical management and rehabilitation. *J Sport Health Sci*. 2021;10(2):154–161. doi:10.1016/j.jshs.2020.11.005
9. Shih Y, Fisher BE, Smith JA, Powers CM. Corticomotor excitability of gluteus maximus is associated with hip biomechanics during a single-leg drop-jump. *J Mot Behav*. 2021;53(1):40–46. doi:10.1080/00222895.2020.1723480
10. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005;33(4):492–501. doi:10.1177/0363546504269591
11. Dubose DF, Herman DC, Jones DL, et al. Lower extremity stiffness changes after concussion in collegiate football players. *Med Sci Sports Exerc*. 2017;49(1):167–172. doi:10.1249/MSS.0000000000001067
12. Lynall RC, Blackburn JT, Guskiewicz KM, Marshall SW, Plummer P, Mihalik JP. Reaction time and joint kinematics during functional movement in recently concussed individuals. *Arch Phys Med Rehabil*. 2018;99(5):880–886. doi:10.1016/j.apmr.2017.12.011
13. Avedesian JM, Covassin T, Dufek JS. Landing biomechanics in adolescent athletes with and without a history of sports-related concussion. *J Appl Biomech*. 2020;36(5):313–318. doi:10.1123/jab.2020-0034
14. Shumski EJ, Kasamatsu TM, Wilson KS, Pamukoff DN. Drop landing biomechanics in individuals with and without a concussion history. *J Appl Biomech*. 2021;37(5):450–457. doi:10.1123/jab.2021-0097
15. Song Y, Li L, Hughes G, Dai B. Trunk motion and anterior cruciate ligament injuries: a narrative review of injury videos and controlled jump-landing and cutting tasks. *Sports Biomech*. 2023;22(1):46–64. doi:10.1080/14763141.2021.1877337
16. Weltin E, Gollhofer A, Mornieux G. Effect of gender on trunk and pelvis control during lateral movements with perturbed landing. *Eur J Sport Sci*. 2016;16(2):182–189. doi:10.1080/17461391.2014.992478
17. Mokha M, Sprague PA, Gatens DR. Predicting musculoskeletal injury in National Collegiate Athletic Association Division II athletes from asymmetries and individual-test versus composite functional movement screen scores. *J Athl Train*. 2016;51(4):276–282. doi:10.4085/1062-6050-51.2.07
18. Lynall RC, Campbell KR, Mauntel TC, Blackburn JT, Mihalik JP. Single-legged hop and single-legged squat balance performance in recreational athletes with a history of concussion. *J Athl Train*. 2020;55(5):488–493. doi:10.4085/1062-6050-185-19
19. Wilkerson GB, Nabhan DC, Crane RT. Concussion history and neuromechanical responsiveness asymmetry. *J Athl Train*. 2020;55(6):594–600. doi:10.4085/1062-6050-0401.19
20. Shumski EJ, Kasamatsu TM, Wilson KS, Pamukoff DN. Mental fatigue uniquely influences drop landing biomechanics for individuals with a concussion history. *J Sport Rehabil*. 2023;32(4):353–360. doi:10.1123/jsr.2022-0252
21. Lapointe AP, Nolasco LA, Sosnowski A, et al. Kinematic differences during a jump cut maneuver between individuals with and without a concussion history. *Int J Psychophysiol*. 2018;132(pt A):93–98. doi:10.1016/j.ijpsycho.2017.08.003

22. Lee BJ, Blueitt D, Hannon J, Goto S, Garrison C. Movement patterns during a jump-landing task in athletes after sport-related concussion and healthy control individuals. *J Athl Train*. 2021;56(12):1306–1312. doi:10.4085/533-20
23. Wesley CA, Aronson PA, Docherty CL. Lower extremity landing biomechanics in both sexes after a functional exercise protocol. *J Athl Train*. 2015;50(9):914–920. doi:10.4085/1062-6050-50.8.03
24. Butler RJ, Willson JD, Fowler D, Queen RM. Gender differences in landing mechanics vary depending on the type of landing. *Clin J Sport Med*. 2013;23(1):52–57. doi:10.1097/JSM.0b013e318259efa0
25. Aizawa J, Hirohata K, Ohji S, Ohmi T, Yagishita K. Limb-dominance and gender differences in the ground reaction force during single-leg lateral jump-landings. *J Phys Ther Sci*. 2018;30(3):387–392. doi:10.1589/jpts.30.387
26. Broglio SP, Kontos AP, Levin H, et al. National Institute of Neurological Disorders and Stroke and Department of Defense Sport-Related Concussion Common Data Elements Version 1.0 recommendations. *J Neurotrauma*. 2018;35(23):2776–2783. doi:10.1089/neu.2018.5643
27. Shumski EJ, Anderson MN, Oh J, Schmidt JD, Lynall RC. Computerized and functional reaction time in varsity level female collegiate athletes with and without a concussion history. *J Sci Med Sport*. 2023;26(3):189–194. doi:10.1016/j.jsams.2023.02.008
28. Bell AL, Brand RA, Pedersen DR. Prediction of hip joint centre location from external landmarks. *Hum Mov Sci*. 1989;8(1):3–16.
29. Lakens D. The 20% statistician: calculating confidence intervals for Cohen's d and eta-squared using SPSS, R, and Stata. Daniellakens Blogspot. Published June 7, 2014. Accessed July 14, 2023. http://daniellakens.blogspot.com/2014/06/calculating-confidence-intervals-for.html
30. Steiger JH. Beyond the F test: effect size confidence intervals and tests of close fit in the analysis of variance and contrast analysis. *Psychol Methods*. 2004;9(2):164–182. doi:10.1037/1082-989X.9.2.164
31. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Front Psychol*. 2013;4:863. doi:10.3389/fpsyg.2013.00863
32. Carson DW, Ford KR. Sex differences in knee abduction during landing. *Sports Health*. 2011;3(4):373–382. doi:10.1177/1941738111410180
33. Ortiz A, Trudelle-Jackson E, McConnell K, Wylie S. Effectiveness of a 6-week injury prevention program on kinematics and kinetic variables in adolescent female soccer players: a pilot study. *P R Health Sci J*. 2010;29(1):40–48.
34. Stearns-Reider KM, Straub RK, Powers CM. Hip abductor rate of torque development as opposed to isometric strength predicts peak knee valgus during landing: implications for anterior cruciate ligament injury. *J Appl Biomech*. 2021;37(5):471–476. doi:10.1123/jab.2020-0398
35. Powers KC, Cinelli ME, Kalmar JM. Cortical hypoexcitability persists beyond the symptomatic phase of a concussion. *Brain Inj*. 2014;28(4):465–471. doi:10.3109/02699052.2014.888759
36. De Beaumont L, Brisson B, Lassonde M, Jolicoeur P. Long-term electrophysiological changes in athletes with a history of multiple concussions. *Brain Inj*. 2007;21(6):631–644. doi:10.1080/02699050701426931
37. De Beaumont L, Théoret H, Mongeon D, et al. Brain function decline in healthy retired athletes who sustained their last sports concussion in early adulthood. *Brain J Neurol*. 2009;132(pt 3):695–708. doi:10.1093/brain/awn347
38. Bodkin SG, Norte GE, Hart JM. Corticospinal excitability can discriminate quadriceps strength indicative of knee function after ACL-reconstruction. *Scand J Med Sci Sports*. 2019;29(5):716–724. doi:10.1111/sms.13394
39. Shih Y, Fisher BE, Kutch JJ, Powers CM. Corticomotor excitability of gluteus maximus and hip extensor strength: the influence of sex. *Hum Mov Sci*. 2021;78:102830. doi:10.1016/j.humov.2021.102830
40. Bates NA, Myer GD, Hale RF, Schilaty ND, Hewett TE. Prospective frontal plane angles used to predict ACL strain and identify those at high risk for sports-related ACL injury. *Orthop J Sports Med*. 2020;8(10):2325967120957646. doi:10.1177/2325967120957646
41. Myer GD, Ford KR, Di Stasi SL, Foss KD, Micheli LJ, Hewett TE. High knee abduction moments are common risk factors for patellofemoral pain (PFP) and anterior cruciate ligament (ACL) injury in girls: is PFP itself a predictor for subsequent ACL injury? *Br J Sports Med*. 2015;49(2):118–122. doi:10.1136/bjsports-2013-092536
42. Dos'Santos T, Thomas C, McBurnie A, Comfort P, Jones PA. Biomechanical determinants of performance and injury risk during cutting: a performance-injury conflict? *Sports Med*. 2021;51(9):1983–1998. doi:10.1007/s40279-021-01448-3
43. Blackburn JT, Padua DA. Sagittal-plane trunk position, landing forces, and quadriceps electromyographic activity. *J Athl Train*. 2009;44(2):174–179. doi:10.4085/1062-6050-44.2.174
44. Eagle SR, Kessels M, Johnson CD, et al. Bilateral strength asymmetries and unilateral strength imbalance: predicting ankle injury when considered with higher body mass in US Special Forces. *J Athl Train*. 2019;54(5):497–504. doi:10.4085/1062-6050-255-18
45. Richmond SA, Kang J, Emery CA. Is body mass index a risk factor for sport injury in adolescents? *J Sci Med Sport*. 2013;16(5):401–405. doi:10.1016/j.jsams.2012.11.898
46. Mendiguchia J, Ford KR, Quatman CE, Alentorn-Geli E, Hewett TE. Sex differences in proximal control of the knee joint. *Sports Med*. 2011;41(7):541–557. doi:10.2165/11589140-000000000-00000
47. Cone SM, Lee S. Lower limb force asymmetries during landing and jumping exercises: a pilot study. *Int J Exerc Sci*. 2021;14(1):544–551.
48. Schmitt LC, Paterno MV, Ford KR, Myer GD, Hewett TE. Strength asymmetry and landing mechanics at return to sport after anterior cruciate ligament reconstruction. *Med Sci Sports Exerc*. 2015;47(7):1426–1434. doi:10.1249/MSS.0000000000000560
49. Aerts I, Cumps E, Verhagen E, Mathieu N, Van Schuerbeeck S, Meeusen R. A 3-month jump-landing training program: a feasibility study using the RE-AIM framework. *J Athl Train*. 2013;48(3):296–305. doi:10.4085/1062-6050-48.3.18
50. Genoese F, Baez SE, Heebner N, Hoch MC, Hoch JM. The relationship between injury-related fear and visuomotor reaction time in individuals with a history of anterior cruciate ligament reconstruction. *J Sport Rehabil*. 2020;30(3):353–359. doi:10.1123/jsr.2019-0511
51. Thompson XD, Newman TM, Donahue CC, Erdman NK, Statuta SM, Resch JE. Kinesiophobia is related to acute musculoskeletal injury incidence following concussion. *J Sport Rehabil*. 2022;32(2):145–150. doi:10.1123/jsr.2022-0134
52. HEADS UP. Returning to sports and activities. Centers for Disease Control and Prevention. Published February 12, 2019. Accessed September 30, 2022. https://www.cdc.gov/headsup/basics/return_to_sports.html
53. May KH, Marshall DL, Burns TG, Popoli DM, Polikandriotis JA. Pediatric sports specific return to play guidelines following concussion. *Int J Sports Phys Ther*. 2014;9(2):242–255.
54. Oldham JR, Howell DR, Knight CA, Crenshaw JR, Buckley TA. Gait performance is associated with subsequent lower extremity injury following concussion. *Med Sci Sports Exerc*. 2020;52(11):2279–2285. doi:10.1249/MSS.0000000000002385
55. D'Lauro C, Jones ER, Swope LM, Anderson MN, Broglio S, Schmidt JD. Under-representation of female athletes in research informing influential concussion consensus and position statements: an evidence review and synthesis. *Br J Sports Med*. 2022;56(17):981–987. doi:10.1136/bjsports-2021-105045
56. Bell DR, Blackburn JT, Hackney AC, Marshall SW, Beutler AI, Padua DA. Jump-landing biomechanics and knee-laxity change across the menstrual cycle in women with anterior cruciate ligament reconstruction. *J Athl Train*. 2014;49(2):154–162. doi:10.4085/1062-6050-49.2.01

57. Balachandar V, Marciniak JL, Wall O, Balachandar C. Effects of the menstrual cycle on lower-limb biomechanics, neuromuscular control, and anterior cruciate ligament injury risk: a systematic review. *Muscles Ligaments Tendons J*. 2017;7(1):136–146. doi:10.11138/mltj/2017.7.1.136

SUPPLEMENTAL MATERIAL

Supplemental Table 1. Jump-Landing Model Characteristics.
Supplemental Table 2. Cutting Model Characteristics.

Found at DOI: https://dx.doi.org/10.4085/1062-6050-0259.23.S1

Address correspondence to Eric J. Shumski, MS, UGA Biomechanics Laboratory, University of Georgia, Ramsey Student Center, 330 River Road, Athens, GA 30602. Address email to eric.shumski@uga.edu.