

Knee Biomechanics in Individuals With a Recent Concussion During Jump-Landing Tasks

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Context: Incomplete neurological recovery following concussion has been linked to increased lower extremity musculoskeletal injury risk. Incorporating cognitive demands into jump-landing tasks may offer better insights into neurological recovery postconcussion and its connection to injury risk.

Objective: To compare unilateral knee biomechanics during jump-landing tasks across different levels of motor and cognitive demands between individuals with a recent concussion and matched controls.

Design: Cross-sectional study.

Setting: Biomechanics laboratory.

Patients or Other Participants: We recruited 26 college students with a recent concussion (22 women; age = 19.7 ± 1.2 years; Tegner scale = 7.0 ± 2.2 ; time since recent concussion = 5.4 ± 3.2 months) and 26 healthy reference participants without a concussion history (22 women; age = 19.9 ± 1.3 years; Tegner scale = 7.0 ± 2.0).

Main Outcome Measure(s): Unilateral and limb symmetry of knee biomechanics were assessed during initial ground contact and the landing phase of jump-landing tasks. Limb symmetry was determined by the absolute difference between limbs for knee flexion and abduction angle, internal knee extension and adduction moments, and vertical and posterior ground

reaction force. Separate repeated-measure analyses of variance with mixed designs examined group, condition, and group-by-condition interaction, with $\alpha = .05$.

Results: No group differences were observed in most outcome measures for either limb or limb symmetry across all jump-landing tasks except that the concussion history group had lower nondominant peak posterior ground reaction force compared with the healthy reference group ($F_{1,50} = 3.461$, $P = .016$, $\eta^2 = 0.111$). Both groups demonstrated higher peak knee flexion, abduction angle, and peak knee adduction moments but lower peak knee extension moments and peak vertical ground reaction force on both limbs during double-leg versus single-leg conditions. No other significant findings were observed.

Conclusions: The concussion history group demonstrated similar knee biomechanical profiles to the healthy reference group during landing even with added cognitive demands in jump-landing tasks. Elevated lower extremity musculoskeletal injury risk postconcussion may not be detectable through jump-landing biomechanics.

Key Words: mild traumatic brain injury, dual task, dynamic maneuvers, sport-related tasks

Key Points

- Individuals with a history of a concussion demonstrate similar jump-landing strategies compared with a healthy reference group across various levels of sport-related tasks.
- The effects of motor and cognitive demands on knee biomechanics were similar between those with and without a prior concussion.
- The current jump-landing progression may have led to a ceiling effect in both groups, highlighting the need for suitable task difficulty to examine knee biomechanics in individuals with prior concussions.

Establishing return-to-play guidelines has been a critical component for concussion management.¹ Although current evidence suggests that most individuals return to play within a month following concussion,² they face an approximately 2.2 times increased risk of lower extremity musculoskeletal injury (LEMI)³ and 1.6 times greater odds of anterior cruciate ligament (ACL) injury⁴ compared with their healthy counterparts. Notably, this increased LEMI risk may persist for 1 to 2 years postconcussion.^{3,4} Neurological recovery may extend beyond return to play following concussion, and this potentially increases LEMI risk after sport resumption.⁵

These findings highlight the persistent effect of concussion on injury susceptibility and the need for continuing research on connections between concussion and elevated LEMI risk.

Although the underlying mechanism remains unclear, impaired neuromuscular control has been proposed as a manifestation of incomplete neurological recovery postconcussion.^{6,7} Studies have investigated sport-related biomechanical assessments using jump-landing tasks in individuals with concussion history aiming to link these subtle lower extremity biomechanical alterations to LEMI risk; however, findings were inconclusive.^{8–12} Authors of some studies suggested

that individuals with a concussion history displayed unfavorable landing profiles, including greater internal knee extension (KEM) and adduction (KAM) moments⁸ along with smaller ankle dorsiflexion angles⁹ during double-leg jump-landing tasks—movement patterns linked to increased ACL injury risks.^{13,14} Additionally, concussion history has been linked to both unilateral and bilateral jump-landing alterations,^{8,15} and asymmetrical KEM during landing was associated with increased ACL injury risk.¹⁶ Although it is unclear whether these asymmetrical movement patterns reflect preexisting conditions or result from concussion-related alterations,^{8,15} these findings suggest that concussion history is related to asymmetrical whole-body movements, which could elevate the risk of ACL injury.

Conversely, others have found comparable jump-landing biomechanical profiles between those with and without a concussion history.^{10,11} Potential explanations for these conflicting results^{8–12} may include variation in data analytic approaches^{9–11} and the difficulty level of motor tasks used across studies.^{10,11} For instance, some studies averaged joint kinetics and kinematics across both limbs,¹¹ whereas others focused solely on 1 tested limb.^{9,10} Averaging across limbs could potentially mask differences in lower extremity biomechanics associated with concussion history. To elucidate biomechanical alteration associated with ACL injury risk in individuals with a concussion history, it is crucial to analyze each limb individually and examine symmetry between limbs. Additionally, consistent evidence has indicated dual-task gait (simultaneously performing gait and cognitive tasks) deficiency in those with a concussion history,^{7,17} suggesting that multitasking dysfunction emerged when motor and cognitive demands increased. Extending this concept to sport-related movements, incorporating cognitive demands into jump-landing tasks may more effectively reveal subtle biomechanical abnormalities. This dual-task approach could assist researchers and clinicians in identifying individuals at greater risk of LEMI following concussion.

The current study aimed to examine if unilateral knee biomechanics and limb symmetry differed between college students with a concussion history and a healthy reference group during jump-landing tasks with different levels of motor and cognitive demands. We hypothesized that the concussion history group would display unfavorable knee biomechanics and greater asymmetry compared with the healthy reference group in all jump-landing tasks. We further hypothesized that the effect of task difficulty on knee biomechanics and symmetry would be greater in the concussion history group.

METHODS

Participants

We recruited 52 physically active college students with 26 participants each in the healthy reference and concussion history groups. The sample size was determined by a priori power analysis using G*Power (version 3.1.9.3; University of Düsseldorf, Germany). Based on a previous study's effect size (0.408)⁸ and repeated-measures analysis of variance (ANOVA) with a mixed design, 25 participants per group were needed to achieve 80% power at $\alpha = .05$ with 2 groups, 4 measurements, and an expected correlation of 0.5. This study received institutional review

board approval at the university. Participants provided their written consent prior to the study session.

The inclusion criteria comprised individuals aged 18 to 25 who self-reported regularly engaging in moderate or vigorous physical activity.¹⁸ Moderate activity was defined as exercise at 3 to 5.9 metabolic equivalents for at least 150 minutes per week.¹⁸ Vigorous activity was defined as exercise above 6 metabolic equivalents for at least 75 minutes per week.¹⁸ Exclusion criteria included more than 3 previous concussions, neurological conditions affecting balance or attention, moderate or severe traumatic brain injuries, a lower extremity injury history requiring surgery, and a recent LEMI (<6 months) that caused more than 3 days of missed physical activity. Participants using medications that affected balance or attention were also excluded. Eligible participants were matched based on sex, age (± 2 years), sports (if participants were collegiate athletes), and Tegner Activity Scale level (± 1). The Tegner Activity Scale is a self-reported questionnaire that evaluates sports-related participation on a 0 to 10 scale, on which 0 represents *maximum disability* and 10 indicates *elite athletic activity*.¹⁹

The healthy reference group self-reported no concussion history, whereas the concussion history group confirmed at least 1 concussion, with the most recent occurring within the past year. A concussion was defined as a mild traumatic brain injury induced by biomechanical forces that are transmitted to the head, sometimes involving loss of consciousness.¹ We enrolled the concussion history group after their clinical recovery, defined as receiving unrestricted medical clearance from health care providers or resuming their pre-injury level of physical activities without experiencing concussive signs or symptoms (Table 1).

Study Procedures

Participants completed an online survey (Qualtrics Inc) to report demographic and clinical information, including sex, age, and concussion and sport history. They also reported their dominant limbs by which leg they preferred to kick a ball as far as possible.¹³

The research staff placed 62 reflective markers on participants. Forty reflective markers were utilized to define the foot, leg, thigh, and pelvis segments. These markers were placed on the following landmarks: (1) foot: medial and lateral calcaneus and first and fifth metatarsal heads (on shoes); (2) leg and thigh: medial and lateral malleoli and femoral epicondyles, lateral shank and thigh with clusters of 4 noncolinear markers, right and left greater trochanter; (3) pelvis: bilateral anterior and posterior iliac spine and ilium crest. Twenty-two reflective markers were utilized to define trunk, arm, forearm, and head segments: (1) trunk: acromioclavicular joint, sternal notch, seventh cervical vertebrae, 10th thoracic vertebrae, and bilateral inferior angle of the scapula; (2) arm and forearm: bilateral medial and lateral humeral epicondyle, the middle portion of the lateral arm and forearm, ulnar and radial styloid process; and (3) head: front, top, and back of the head (on hat).

Participants then performed 4 jump-landing conditions: double leg, single leg, and 2 levels of single leg with cognitive demands. Tasks increased in difficulty, progressing from double leg to single leg with cognitive demands. Participants completed at least 3 practice trials, followed by 3

Table 1. Demographic Information for the Healthy Reference and Concussion History Groups

Demographics	Healthy Reference Group, n = 26	Concussion History Group, n = 26
Age, y ^a	19.9 (1.3)	19.7 (1.2)
Sex, female ^b	22 (84.6)	22 (84.6)
Height, cm ^a	169.7 (8.8)	169.1 (9.0)
Weight, kg ^a	68.5 (10.2)	68.7 (10.2)
Dominant leg, right ^b	25 (96.1)	25 (96.1)
Tegner Scale ^a	7 (2.2)	7 (2.0)
Collegiate athletes ^b	7 (26.9)	7 (26.9)
Number of previous concussions ^b		
1	—	11 (42.3)
2	—	8 (30.8)
3	—	7 (26.9)
Time since most recent concussion, mo ^{a,c}	—	5.4 (3.2)
Recovery time of most recent concussion, d ^{a,d}	—	17.3 (13.4)

^a Data presented as mean (SD).

^b Data presented as number (%).

^c Time since most recent concussion was calculated as the days between concussion and study section.

^d Recovery time of most recent concussion was calculated as the days between concussion and either receiving medical clearance or returning to preinjury activity level.

successful trials for each condition with at least 30 seconds of rest between trials. Successful trials required participants to jump forward (not upward) from the box to the landing area, jump off the box with both limbs simultaneously, land with 1 foot entirely on 1 force plate, and complete the task smoothly. The order of tasks was counterbalanced and matched between groups.

Jump-Landing Task Procedures

The jump-landing setup is presented in Figure 1. To standardize visual stimuli across conditions, a 48-inch television displayed visual targets for participants. For both double- and single-leg conditions, a controlled visual target (“+” sign) was used, whereas flanker figures were used for the single leg with cognitive demands.

In the double-leg condition, participants stood on a 30-cm box positioned at 50% of their height behind the force plate,

jumped forward with both limbs simultaneously, and landed on 2 force plates (1 foot on each).^{20,21} Upon landing, participants performed a vertical jump for maximum height.^{20,21} The single-leg condition followed the same jump-landing procedure with 2 adjustments: (1) the distance between the force plate and box was reduced to 25% of the participant’s height, and (2) participants landed on 1 leg on a single force plate.²¹ Both limbs were assessed in the single-leg condition.

In the single-leg with cognitive demands condition, participants completed the single-leg condition²¹ combined with the Arrow Flanker Test, which involved 2 levels of cognitive demands: congruent (≪≪≪ or ≫≫≫) and incongruent (≪≪≫ or ≫≪≪) conditions.²² We considered the incongruent condition as more challenging due to slower reaction times and higher error rates compared with the congruent condition.²² Participants were instructed to land on the limb indicated by the central arrow on the flanker figure. A customized LabView script (LabView, National

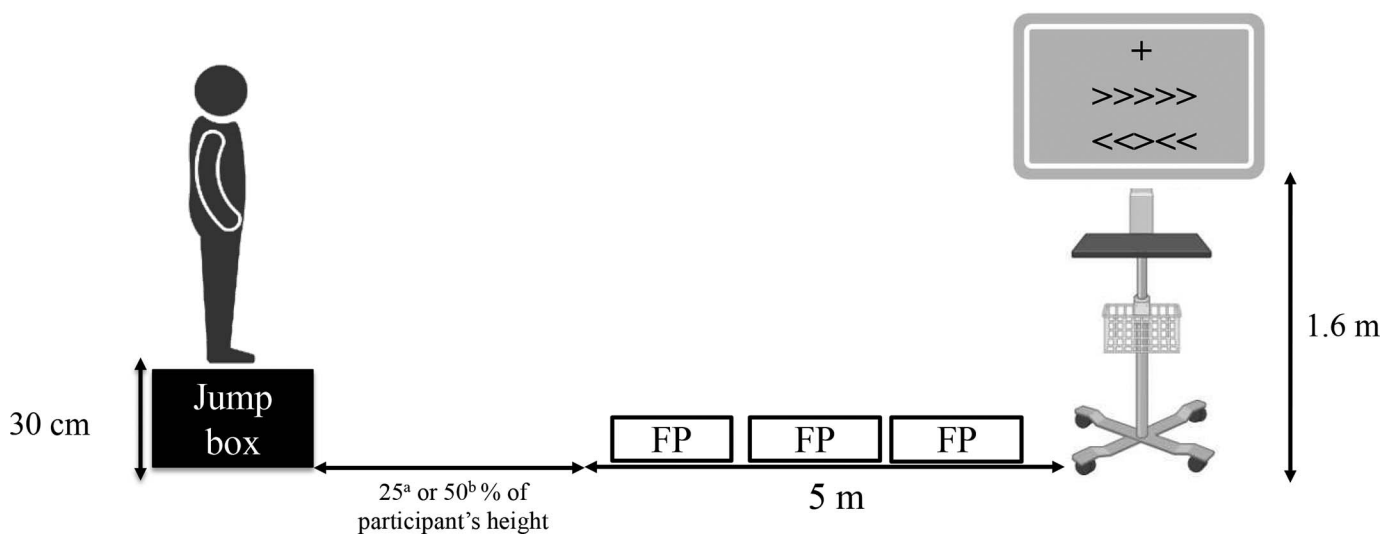


Figure 1. Jump-landing task set-up and examples of visual target presentations including the “+” sign and arrow flanker figures. Abbreviation: FP, force plate. ^aFor single-leg and single-leg with cognitive demands condition, the jump box was placed 25% of participant’s height away from the force plate. ^bFor double-leg condition, the jump box was placed 50% of participant’s height away from the force plate.

Table 2. Outcome Measures Associated With Anterior Cruciate Ligament Injury Risk^a

Sagittal Plane Variables	Frontal Plane Variables
Knee flexion angle ^b ↓	Knee abduction angle ^b ↑
Peak knee flexion angle ^c ↓	Peak knee abduction angle ^c ↑
Internal knee extension moment ^b ↑	Internal knee adduction moment ^b ↑
Peak internal knee extension moment ^c ↑	Peak internal knee adduction moment ^c ↑
Peak vertical ground reaction force ^c ↑	
Peak posterior ground reaction force ^c ↑	

^a The arrow indicates the unfavorable direction (greater injury risk) of each variable.

^b Values at initial ground contact.

^c Peak values between initial ground contact and 100 ms after initial ground contact.

Instruments) was used to synchronize the motion capture system and trigger the flanker figure display. Through pilot testing, we determined figures should appear when the front head marker moved anteriorly by 6% of the participant's height (cm) from its initial position. This initial position was identified while the participant stood on the box before jumping. As the jump began, a flanker figure was displayed, prompting participants to make an immediate decision on which limb to land.

Instrumentation and Data Reduction

We utilized a 12-camera optical motion capture system collecting at 120 Hz (Qualisys), along with 3 adjacent force plates collecting data at 1200 Hz (AMTI Inc). Data were processed using Visual 3D (HAS-Motion). We filtered marker and ground reaction force (GRF) data using a fourth-order low-pass Butterworth filter with cutoff frequencies of 12 and 50 Hz, respectively. Marker data were used to create a static calibration model of the entire body, including the head and neck, trunk, pelvis, arms, forearms, thighs, shanks, and feet. The centers for the ankle and knee joints were identified using the midpoints of the medial and lateral malleoli and femoral epicondyles, respectively. The hip joint center was determined using the Bell Method.²³ Joint angles were defined as motions of distal segments relative to the proximal segments and were calculated using a Cardan x-y-z rotation sequence (sagittal, frontal, transverse). Internal joint moments were computed using Newton-Euler equations in the proximal body segment coordinate system to estimate net muscular effort required to produce or resist joint motion. Joint moments were normalized by the product of body weight and height, whereas GRF data were normalized by body weight (%BW).

Primary Outcome Measures

Building upon previous studies investigating knee biomechanics associated with ACL injury risk, we identified variables at initial contact (IC) and peak values within 100 milliseconds post-IC.^{13,14,24} We defined the IC when the vertical GRF (vGRF) exceeded 10 N. Table 2 summarizes the unfavorable direction of outcome measures. Limb symmetry of each variable was calculated as the absolute difference between the dominant and nondominant limbs.

Secondary Outcome Measures

Incorporating cognitive demands into motor tasks challenges individuals to optimize motor and cognitive performance, often resulting in dual-task interference characterized by reduced motor or cognitive performance or both.²⁵ To determine whether the concussion history group prioritized safer landing strategies, we compared cognitive accuracy, movement initiation time, and jump height between groups. Safe landing strategies were defined as lower cognitive accuracy, longer movement initiation times, and reduced jump heights (cognitive accuracy [%]: the number of correct landings [landing on the indicated limb] divided by the total number of attempts in the single-leg task with cognitive demands, movement initiation time [s]: the time between the anterior head and first toe markers moving anteriorly by 2 SDs from their initial positions, and jump height [cm]: the vertical distance between the highest point and the initial position of the center of mass). Initial positions for markers and center of mass were identified when participants stood on the box before initiating jump-landing tasks.

Greater trunk flexion (TF) during jump landing has been associated with attenuating impact forces, including lower vGRF and a potential trend toward lower posterior GRF (pGRF).²⁶ Previous research has also indicated that individuals with previous concussions demonstrated greater TF at IC compared with matched controls during jump-cutting tasks,¹⁰ suggesting that individuals with a previous concussion may utilize a landing posture emphasizing TF, potentially mitigating impact forces. To investigate the effect of TF on kinetic measures, we compared TF at IC and peak TF between groups. Trunk motion was defined as the motion of the trunk segment relative to the laboratory axis system.

Statistical Analysis

All analyses were conducted using SPSS (version 28; IBM) with mean values calculated across trials for each limb of each participant. The residuals of outcome measures were normally distributed as examined by a Shapiro-Wilk test. Separate 2 (group) × 4 (condition) repeated-measure ANOVAs were used to examine the effect of prior concussion, jumping condition, and their interaction on each primary outcome measure for dominant and nondominant limbs and the symmetry between limbs. Additionally, movement initiation time, jump height, and TF were compared between groups using the same repeated-measure ANOVAs. Cognitive accuracy was examined between groups under 2 (group) × 2 (condition) repeated-measure ANOVAs. An alpha level of .05 was set a priori for all analyses. When significant interactions or task effects were identified, post hoc tests with Bonferroni correction were conducted. For significant interaction effects, post hoc tests compared groups within the 4 jump-landing conditions. Partial eta squared effect sizes were interpreted as small (<0.06), medium (0.06–0.14), or large (≥0.14).²⁷

RESULTS

Demographic information is presented in Table 1. Due to the demanding nature of the single-leg with cognitive demands condition and technical challenges, 2 participants in the concussion history group completed only 2 and 1

Table 3. Jump-Landing Outcomes Between Groups^a

	Healthy Reference Group, n = 26		Concussion History Group, n = 26	
	Dominant	Nondominant	Dominant	Nondominant
Panel A. Jump-Landing Outcomes During the Double-Leg Condition				
Initial ground contact				
KF, °	-20.7 (6.5)	-22.0 (8.2)	-21.3 (5.4)	-20.6 (6.7)
KAB, °	0.7 (3.6)	2.6 (3.8)	1.1 (4.8)	3.1 (3.9)
KEM, % BW × HT	-0.001 (0.017)	-0.003 (0.015)	-0.004 (0.015)	-0.010 (0.013)
KAM, % BW × HT	0.011 (0.008)	0.008 (0.007)	0.007 (0.008)	0.010 (0.007)
Peak ^b				
KF, °	-72.9 (6.4)	-72.7 (6.2)	-73.1 (5.0)	-71.8 (6.8)
KAB, °	-6.9 (5.5)	-6.6 (6.0)	-6.2 (5.5)	-5.0 (5.8)
KEM, % BW × HT	0.15 (0.02)	0.14 (0.02)	0.16 (0.03)	0.14 (0.03)
KAM, % BW × HT	0.029 (0.015)	0.029 (0.013)	0.028 (0.016)	0.028 (0.015)
vGRF, % BW	3.05 (0.52)	2.86 (0.49)	2.8 (0.41)	2.50 (0.42)
pGRF, % BW	-0.67 (0.08)	-0.58 (0.08)	-0.64 (0.09)	-0.56 (0.08)
Panel B. Jump-Landing Outcomes During the Single-Leg Condition				
Initial ground contact				
KF, °	-10.9 (5.4)	-11.4 (5.6)	-10.4 (4.1)	-10.0 (5.5)
KAB, °	-1.0 (3.6)	0.6 (2.7)	-0.5 (3.6)	0.5 (4.0)
KEM, % BW × HT	-0.017 (0.012)	-0.012 (0.015)	-0.012 (0.010)	-0.014 (0.014)
KAM, % BW × HT	0.006 (0.007)	0.005 (0.006)	0.005 (0.005)	0.007 (0.006)
Peak ^b				
KF, °	-51.5 (5.3)	-51.4 (6.1)	-53.5 (5.3)	-51.4 (5.8)
KAB, °	-3.1 (3.9)	-2.3 (4.3)	-1.7 (3.8)	-1.1 (4.7)
KEM, % BW × HT	0.17 (0.02)	0.18 (0.02)	0.18 (0.03)	0.17 (0.03)
KAM, % BW × HT	0.018 (0.014)	0.019 (0.016)	0.015 (0.014)	0.14 (0.014)
vGRF, % BW	4.36 (0.57)	4.29 (0.61)	4.14 (0.51)	4.14 (0.54)
pGRF, % BW	-0.69 (0.13)	-0.70 (0.10)	-0.67 (0.10)	-0.66 (0.10)
Panel C. Jump-Landing Outcomes During the Single-Leg Arrow Flanker Congruent Condition				
Initial ground contact				
KF, °	-10.8 (4.6)	-11.3 (5.9)	-10.2 (3.7)	-9.9 (5.6)
KAB, °	-0.7 (3.5)	0.6 (3.3)	-0.5 (3.7)	0.4 (4.1)
KEM, % BW × HT	-0.015 (0.014)	-0.010 (0.014)	-0.015 (0.011)	-0.015 (0.012)
KAM, % BW × HT	0.006 (0.007)	0.006 (0.006)	0.004 (0.007)	0.006 (0.006)
Peak ^b				
KF, °	-52.0 (5.6)	-51.8 (5.4)	-52.7 (5.1)	-50.8 (5.4)
KAB, °	-3.2 (4.5)	-2.8 (4.4)	-2.3 (4.1)	-1.5 (4.8)
KEM, % BW × HT	0.17 (0.03)	0.17 (0.02)	0.17 (0.03)	0.17 (0.02)
KAM, % BW × HT	0.020 (0.018)	0.020 (0.017)	0.019 (0.018)	0.016 (0.014)
vGRF, % BW	4.48 (0.63)	4.47 (0.73)	4.32 (0.48)	4.23 (0.52)
pGRF, % BW	-0.70 (0.10)	-0.71 (0.12)	-0.64 (0.13)	-0.63 (0.09)
Panel D. Jump-Landing Outcomes During the Single-Leg Flanker-Incongruent Condition				
Initial ground contact				
KF, °	-10.3 (4.9)	-11.1 (6.0)	-9.7 (3.9)	-10.4 (4.9)
KAB, °	-0.7 (3.4)	0.7 (3.3)	-0.3 (3.5)	0.04 (4.0)
KEM, % BW × HT	-0.013 (0.014)	-0.013 (0.014)	-0.016 (0.011)	-0.015 (0.015)
KAM, % BW × HT	0.005 (0.008)	0.003 (0.006)	0.003 (0.005)	0.005 (0.006)
Peak ^b				
KF, °	-52.0 (6.0)	-52.0 (6.3)	-52.9 (4.9)	-50.8 (5.1)
KAB, °	-3.5 (4.1)	-2.5 (4.5)	-2.0 (4.4)	-1.4 (4.7)
KEM, % BW × HT	0.17 (0.03)	0.17 (0.02)	0.17 (0.03)	0.17 (0.02)
KAM, % BW × HT	0.019 (0.016)	0.018 (0.015)	0.015 (0.017)	0.014 (0.014)
vGRF, % BW	4.51 (0.67)	4.33 (0.64)	4.32 (0.38)	4.25 (0.53)
pGRF, % BW	-0.72 (0.14)	-0.70 (0.12)	-0.66 (0.09)	-0.63 (0.09)

Abbreviations: BW, body weight; HT, height; KAB, knee abduction angle; KAM, internal knee adduction moment; KEM, internal knee extension moment; KF, knee flexion angle; pGRF, posterior ground reaction force; vGRF, vertical ground reaction force.

^a Data presented as mean (SD). Positive values indicate extension and adduction angle/internal moment as well as anterior ground reaction force.

^b Peak values between initial ground contact and 100 ms after initial ground contact.

successful trials for this condition, respectively. We included their successful trials in the analyses.

The results for each jump-landing condition are listed in Table 3. The group effect indicated that the nondominant limb

peak pGRF was lower for the concussion history group compared with the healthy reference group (concussion history = -0.62 ± 1.0 %BW, healthy reference = -0.67 ± 1.2 %BW, $F_{1,50} = 6.271$, $P = .016$, $\eta^2 = 0.111$; Figure 2). No significant

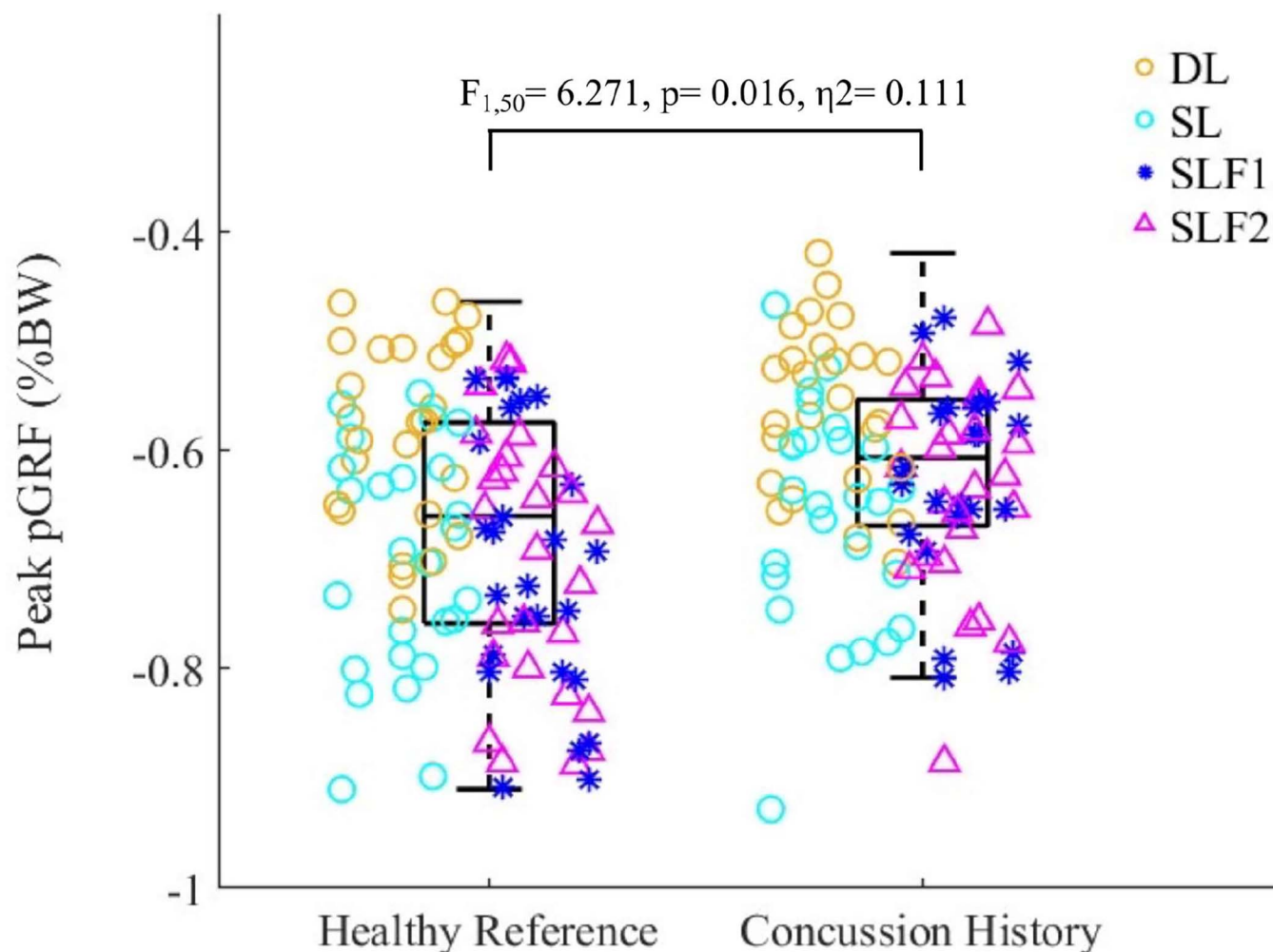


Figure 2. The group effect indicated that the peak pGRF of the nondominant limb peak pGRF was lower for concussion history group compared with the healthy reference group (concussion history = $-0.62 \pm 1.0\%$ body weight [BW], healthy reference = $-0.67 \pm 1.2\%$ BW, $F_{1,50} = 6.271$, $P = 0.016$, $\eta^2 = 0.111$). Abbreviations: DL, double-leg; pGRF, posterior ground reaction force; SL, single-leg; SLF1, single-leg with flanker congruent; SLF2, single-leg with flanker incongruent.

group-by-condition interaction effects were identified for any outcome measures on either limb (Supplementary Material 1).

Significant task effects were observed across most outcome measures for both limbs, except for dominant limb peak pGRF (Supplementary Material 1). Post hoc analyses indicated that, during double-leg conditions compared with the 3 single-leg conditions, participants displayed greater dominant limb knee flexion (KF), KEM, and KAM at IC as well as greater peak KF, peak knee abduction (KAB), and peak KAM (all $P \leq .036$). Similar patterns were observed on nondominant limbs, with greater values for these variables during double-leg conditions compared with the 3 single-leg conditions (all $P < .001$) except for KEM at IC. Participants demonstrated greater KEM at IC during the double-leg condition compared with the single-leg with the flanker-incongruent condition. Additionally, participants had smaller dominant limb KAB at IC, peak KEM, and peak vGRF during double-leg conditions compared with the 3 single-leg conditions (all $P \leq .013$). A similar reduction in the nondominant limb KAB at IC, peak KEM, peak vGRF, and peak pGRF was observed during double-leg conditions compared with the 3 single-leg conditions (all $P \leq .011$). There were no differences between single-leg conditions.

No significant group-by-condition interaction nor group effects were identified for limb symmetry of any outcome measures (Supplementary Material 1). We observed a task effect for the symmetry of peak KAM ($F_{3,150} = 3.386$, $P = .020$, $\eta^2 = 0.063$). The post hoc analysis indicated that more asymmetrical peak KAM was observed during the single-leg flanker congruent condition compared with the double-leg condition ($P = .022$).

Secondary analyses indicated no significant group differences in cognitive accuracy ($P > .647$), movement initiation time ($P > .817$), and jump height ($P > .879$; Supplementary Material 2). Both groups demonstrated comparable TF at IC. However, the healthy reference group demonstrated greater peak TF during landing compared with the concussion history group on both dominant (healthy reference = $17.2^\circ \pm 8.5^\circ$, concussion history = $12.6^\circ \pm 7.2^\circ$, $P = .031$) and nondominant (healthy reference = $17.0^\circ \pm 7.7^\circ$, concussion history = $13.0^\circ \pm 7.1^\circ$, $P = .023$) limbs.

DISCUSSION

The current study aimed to examine the effect of concussion history on knee biomechanics across jump-landing

tasks. Our main results suggest limited differences in knee biomechanics associated with ACL injury risk between healthy reference and concussion history groups for either limb, and no limb asymmetry was observed between groups. Interestingly, the concussion history group displayed lower nondominant limb peak pGRF compared with the healthy reference group across all jump-landing tasks; however, this was the only significant group difference. These findings do not support our hypothesis that the potential incomplete neurological recovery postconcussion is reflected in knee biomechanical alterations during jump-landing tasks. Additionally, both groups displayed unfavorable knee biomechanics in more motor-challenging conditions (single- versus double-leg conditions); however, adding cognitive demands into the single-leg jump-landing task did not further worsen their biomechanical profiles. Thus, the effect of different levels of motor and cognitive demands on jump-landing biomechanics was similar between groups. Collectively, our findings indicate that individuals with a recent concussion (average of 5.4 months) could demonstrate comparable landing strategies as their matched controls when they are clinically recovered.

Jump-Landing Biomechanics Comparison Between Groups

Previous studies have suggested that single-leg jump-landing tasks¹¹ or adding cognitive demands into jump-landing tasks^{10,11} may more effectively detect lower extremity biomechanical alterations associated with concussion history. For instance, Lapointe et al (2018)²⁸ observed that individuals with a concussion history demonstrated smaller peak KF and greater peak KAB compared with matched controls during single-leg jump-cutting tasks combined with the Arrow Flanker Test. However, despite extensively examining knee biomechanics in individuals with recent concussions and matched controls across various levels of sport-related tasks, we observed no group differences in most outcome measures. The inconsistent findings between ours and the previous study may be attributed to variations in jump-landing protocols (forward jump landing on the dominant or nondominant limb versus jump-cutting tasks on the dominant limb only), the timing of flanker figure presentation (6% of anterior displacement of the front head marker versus 0.5 s prior to ground contact), and sex distribution (85% versus 40% were female).²⁸ Alternatively, our participants may not have concussion-related alterations in knee biomechanics, or any related alterations may have resolved by the time of assessment.

Secondary analyses indicated no group differences in cognitive accuracy, movement initiation time, and jump height. Additionally, the healthy reference group demonstrated greater peak TF during landing compared with the concussion history group. These findings suggest that the concussion history group neither prioritized a safer landing strategy nor utilized a landing posture emphasizing TF to mitigate impact forces. Previous research has linked greater TF to a tendency toward lower peak pGRF, suggesting that the healthy reference group might display lower pGRF than the concussion history group.²⁶ However, our finding did not align with this trend.²⁶ To contextualize our findings, we compared them with established normative values and physically active populations. Turner et al (2024)²⁹ reported a normative

knee kinematics range for double-leg jump-landing tasks in cadets. The knee kinematics of our participants fell within the 50% interquartile range reported for the same jump-landing protocol, indicating that both groups displayed knee joint angles within the normative range.²⁹ Additionally, McNair et al (1999)³⁰ established normative values of vGRF during jump-landing tasks in adolescents ($4.5\% \pm 1.7\%$ BW), and Heebner et al (2017)³¹ reported knee biomechanics across a different jump-landing task in military service members. Although the protocols in these studies^{30,31} differed from ours, the vGRF and pGRF observed in our study were similar (Table 3). Therefore, whereas the concussion history group demonstrated statistically significant lower nondominant limb peak pGRF compared with the healthy reference group (average of 5% BW difference), this difference may not be clinically significant. Overall, both groups displayed knee biomechanics consistent with normative values and those observed in physically active populations, supporting our aforementioned suggestions that any concussion-related alterations in knee biomechanics, if present, may have resolved.

To further investigate, exploratory analysis revealed that the number of previous concussions accounted for 40.1% of the variance in nondominant limb peak pGRF ($R^2 = 0.401$, $\beta = -0.633$, $P = .011$). This finding suggests that a greater number of previous concussions is associated with lower peak pGRF. Although the mechanism underlying this association is unclear, it indicates that the number of concussions or concussion history affects GRF outcomes. Future research should include the number of prior concussions as a covariate and recruit a larger sample with broader ranges of concussion history to further investigate this relationship.

Symmetry of Jump-Landing Biomechanics

Contrary to our hypothesis, there were no differences in limb asymmetry between groups. Paterno et al (2010)¹⁶ reported that athletes suffering a second ACL injury following the initial ACL reconstruction have a 4.1 times greater asymmetrical KEM at IC than those without recurrent injury. Several studies have indicated that concussion history is associated with unilateral and bilateral movement alterations, potentially resulting from neurophysiological alterations following concussion.^{8,15} A recent study found that college students with a history of concussion rely heavily on visual and vestibular feedback during postural control assessments compared with control groups.³² The authors suggested that this increased sensory reliance may represent a compensatory mechanism (sensory reweighting), enabling them to regulate sensorimotor integration to restore or maintain function during motor tasks.³² Our concussion history group may have utilized a similar compensatory mechanism during jump-landing tasks. However, without including visual or vestibular perturbations in the current study, we can only speculate about the role of this compensatory mechanism. Future studies incorporating visual and/or vestibular perturbations into jump-landing tasks could offer insights into sensorimotor integration in individuals with prior concussions during sport-related tasks.

The Effect of Task Demands on Jump-Landing Biomechanics

Consistent with previous studies,^{31,33} both groups displayed unfavorable jump-landing biomechanics in motor-challenging

conditions. However, contrary to previous studies,^{34,35} adding cognitive demands to single-leg jump landing did not worsen biomechanics. Taylor et al (2016)³³ reported that recreationally active females use a stiffer landing strategy (eg, smaller peak KF, greater KEM and KAM) in single-leg versus double-leg jump landing. Similarly, Dai et al (2018)³⁴ found that incorporating working memory tests into double-leg jump landings led to smaller KF at IC and higher peak vGRF in healthy college athletes compared with the condition without cognitive demands. These studies^{31,33–35} suggested that increasing motor or adding cognitive demands during jump-landing tasks exacerbates ACL injury risk by reducing sagittal knee kinematics and increasing impact forces. Different from the previous study incorporating cognitive demands into double-leg jump-landing tasks,³⁴ our study focused on single-leg tasks, which inherently place greater demands on the landing limb, requiring more balance, stability, and control. Additionally, participants were instructed to jump forward off the box with both feet simultaneously and land on a single limb. It is possible that our single-leg condition may have already posed a substantial challenge for both groups, potentially creating a ceiling effect. This could explain why adding cognitive demands to the single-leg jump landing did not further worsen jump-landing biomechanics.

Limitations

Several limitations should be considered when interpreting the current findings. Self-reported questionnaires for concussion and LEMI history are prone to recall bias. To mitigate this bias, we provided definitions and concussion signs and symptoms, and a research staff member assisted participants with completing the questionnaires. Whereas participants were recruited within a year of their most recent concussion to minimize variability, the number of prior concussions was not included in the main analysis. Our exploratory analysis suggested that the number of previous concussions accounted for 40.1% of the variance in peak pGRF on the nondominant limbs. Future studies may consider including the number of previous concussions into the analysis for a better understanding of movement alterations following concussion. Lastly, as most participants were female (85%) and physically active college students, our findings may not generalize to other ages, sexes, or activity levels.

CONCLUSION

Our findings indicated that both groups demonstrated comparable knee biomechanics across jump-landing tasks with different motor and cognitive demands. Additionally, participants with a recent concussion demonstrated jump-landing biomechanics within the normative ranges. To deepen our understanding, future prospective studies should recruit a larger sample with a broader range of concussion histories and examine multiple jump-landing tasks before and after concussion, ideally tracking biomechanical alterations across the recovery timeline. This approach could offer clearer insights into the relationship between concussion history and jump-landing biomechanics.

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SUPPLEMENTAL MATERIAL

Supplementary Material 1. 1a) interactions and main effects for four jump-landing outcomes on dominant legs between the groups, 1b) interactions and main effects for four jump-landing outcomes on non-dominant legs between the groups, 1c) interactions and main effects for the symmetry of four jump-landing outcomes between the groups.

Supplementary Material 2. 2a) The cognitive accuracy for the single-leg with cognitive demands condition, 2b) Movement initiation time for four jump-landing condition between groups, 2c) Jump-height for four jump-landing condition between groups, 2d) Trunk flexion for four jump-landing condition between groups.

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