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Title: Knee Biomechanics in Individuals with a Recent Concussion during Jump-Landing Tasks

Author: Tsung-Yeh Chou, PhD, ATC[1]; Email: Jacky8243@gmail.com; Twitter/X: @TsungYeh3 · Yu-Lun Huang, PhD, ATC[2]; Email: huanyulu@ntnu.edu.tw · Thomas A. Buckley, EdD, ATC[1]; Email: tbuckley@udel.edu; Twitter/X: @atcbuck · Jocelyn F. Hafer[1]; Email: jfhafer@udel.edu; Twitter/X: @JocelynHafer · Thomas W. Kaminski, PhD, ATC, FNAK, FNATA[1]; Email: kaminski@udel.edu; Twitter/X: @UD_ATEP

Affiliations: [1]University of Delaware, Department of Kinesiology and Applied Physiology, Newark, DE, USA · [2]National Taiwan Normal University, Department of Physical Education and Sport Science, Taipei, Taiwan

Corresponding author: Thomas W. Kaminski; Email: kaminski@udel.edu; Phone: 302-831-6402; Address: 541 South College Avenue, Newark, DE 19716 (Human Performance Lab - Room 159)

ORCID ID: Tsung-Yeh Chou (0000-0003-4429-0604) · Yu-Lun Huang (0000-0003-0809-3152) · Thomas A. Buckley (0000-0002-0515-0150) · Jocelyn F. Hafer (0000-0002-4178-8872) · Thomas W. Kaminski (0000-0003-0924-0978)

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Author contributions

All listed authors have been involved in the conception, design, acquisition, analysis, and interpretation of data, as well as in drafting and revising the manuscript constructively for important intellectual content.

Competing Interests

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Abstract

Context: Incomplete neurological recovery following concussion has been linked to increased lower extremity musculoskeletal injury (LEMI) risk. Incorporating cognitive demands into jump-landing tasks may offer better insights into neurological recovery post-concussion 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 cohort study

Setting: Biomechanics laboratory

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

Main Outcome Measure: 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, vertical, and posterior ground reaction force (pGRF). Separate repeated measure ANOVAs with mixed designs examined group, condition, and group-by-condition interaction, with $\alpha=0.05$.

Results: No group differences were observed in most outcome measures for either limb or limb symmetry across all jump-landing tasks, except the concussion history group had lower non-dominant peak pGRF compared to healthy reference group ($F_{1,50}= 3.461$, $p= 0.016$, $\eta2= 0.111$). Both groups demonstrated higher peak knee flexion, abduction angle, and peak knee adduction moments, but lower peak knee extension moment, 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 healthy reference group during landing, even with added cognitive demands in jump-landing tasks. Elevated LEMI risk post-concussion may not be detectable through jump-landing biomechanics.

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

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Key Points: (1) Individuals with a history of a concussion demonstrate similar jump-landing strategies compared to a healthy reference group across various levels of sport-related tasks. (2) The effects of motor and cognitive demands on knee biomechanics were similar between those with and without a prior concussion. (3) 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.

Introduction

Establishing return-to-play (RTP) guidelines has been a critical component for concussion management.[1] Although current evidence suggests that most individuals RTP within a month following concussion,[2] they face approximately 2.2 times increased risk of lower extremity musculoskeletal injury (LEMI)[3] and 1.6 times greater odds of anterior cruciate ligament (ACL) injury[4] compared to their healthy counterparts. Notably, this increased LEMI risk may persist for 1-2 years post-concussion.[3,4] Neurological recovery may extend beyond RTP following concussion, which potentially increased 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 post-concussion.[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] Some studies suggested that individuals with concussion history displayed unfavorable landing profiles including greater internal knee extension (KEM) and adduction (KAM) moments,[8] along with smaller ankle dorsiflexion angles[9] 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 pre-existing conditions or result from concussion-related alterations,[8,15] these findings suggested that concussion history was 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 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] while others focused solely on one 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 individual with concussion history, it is crucial to analyze each limb individually and examine symmetry between limbs. Additionally, consistent evidence has indicated that dual-task gait (simultaneously performing gait and cognitive tasks) deficiency in those with concussion history,[7,17] suggesting that multitasking dysfunction merged 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 to identify individuals at greater risk of LEMI post-concussion.

The current study aimed to examine if unilateral knee biomechanics and limb symmetry differed between college students with a concussion history and 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 to 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 mixed design, 25 participants per group were needed to achieve 80% power at $\alpha = 0.05$, 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 consents prior to study session.

The inclusion criteria comprised individuals aged 18 to 25 who self-reported regularly engaged in moderate or vigorous physical activity.[18] Moderate activity was defined as exercise at 3 to 5.9 METs for at least 150 minutes per week.[18] Vigorous activity was defined as exercise above 6 METs for at least 75 minutes per week.[18] Exclusion criteria included more than three previous concussions, neurological conditions affecting balance or attention, moderate or severe traumatic brain injuries, a lower extremity injury history requiring surgery, and recent LEMI (< 6 months) that caused more than three 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 0-10 scale, where 0 represents maximum disability and 10 indicates elite athletic activity.[19]

The healthy reference group self-reported no concussion history, while the concussion history group confirmed at least one 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 following their clinical recovery, defined as receiving unrestricted medical clearance from healthcare 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, Provo, UT) to report demographic and clinical information, including sex, age, and concussion and sport history. They also reported their dominant limbs by which leg they prefer to kick a ball as far as possible.[13]

The research staff placed 62 reflective markers on participants. 40 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 1st and 5th metatarsal heads (on shoes), 2) leg and thigh: medial and lateral malleoli and femoral epicondyles, lateral shank and thigh with clusters of four noncolinear markers, right and left greater trochanter, 3) pelvis: bilateral anterior and posterior iliac spine, and ilium crest. 22 reflective markers were utilized to define trunk, arm, forearm, and head segments: 1) trunk: acromioclavicular joint, sternal notch, 7th 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 four jump-landing conditions: double-leg, single-leg, and two 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 three practice trials, followed by three 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 one foot entirely on one 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 two force plates (one 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 two adjustments: (1) the distance between force plate and box was reduced to 25% of participant's height, and (2) participants landed on one 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 condition[21] combined with the Arrow Flanker Test, which involved two 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 to 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 Instruments, Austin, TX) 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 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, Santa Rosa, CA), along with three adjacent force plates collecting data at 1200 Hz. (AMTI Inc, Watertown, MA, USA). Data were processed using Visual 3D (HAS-Motion, Ontario, Canada). 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 was used to create a static calibration model of entire body, including head-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, while GRF data was 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 ground reaction force (vGRF) exceeded 10 newtons. Table 2 summarizes the unfavorable direction of outcome measures. Limb symmetry of each variable was calculated as the absolute difference between dominant and non-dominant 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 landing (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 1st toe markers moving

anteriorly by two standard deviations from their initial positions. 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 ground reaction force (pGRF).[26] Previous research has also indicated that individuals with previous concussions demonstrated greater TF at IC compared to matched controls during jump-cutting tasks,[10] suggesting that individuals with a previous concussion may utilized 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 trunk segment relative to the laboratory axis system.

Statistical Analysis

All analyses were conducted using SPSS version 28 (IBM, Armonk, NY), with mean values calculated across trials for each limb of each participant. The residuals of outcome measures were normally distributed as examined by Shapiro–Wilk test. Separate 2 (group) x 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 non-dominant 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) x 2 (condition) repeated measure ANOVAs. An alpha level of 0.05 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 four 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, two participants in the concussion history group completed only 2 and 1 successful trials for this condition, respectively. We included their successful trials in analyses.

The results for each jump-landing condition are listed in Table 3. The group effect indicated that the non-dominant limb peak pGRF was lower for concussion history group compared to healthy reference group (concussion history= -0.62 ± 1.0 %BW, healthy reference= -0.67 ± 1.2 %BW, $F_{1,50}$= 6.271, p= 0.016, η2= 0.111) (Figure 2). No significant 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 to the three 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≤ 0.036). Similar patterns were observed on non-dominant limbs, with greater values for these variables during double-leg conditions compared to the three single-leg conditions (all p< 0.001), except for KEM at IC. Participants demonstrated greater KEM at IC during the double-leg condition compared to the single-leg with flanker incongruent condition. Additionally, participants had smaller dominant limb KAB at IC, peak KEM, and peak vGRF during double-leg conditions compared to three single-leg conditions (all p≤ 0.013). A similar reduction in non-dominant limb KAB at IC, peak KEM, peak vGRF, and peak pGRF was observed during double-leg conditions compared to three single-leg conditions (all p≤ 0.011). 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= 0.020, η2= 0.063). The post-hoc analysis indicated more asymmetrical peak KAM was observed during single-leg flanker congruent condition compared to the double-leg condition (p= 0.022).

Secondary analyses indicated no significant groups differences in cognitive accuracy (p> 0.647), movement initiation time (p> 0.817), and jump-height (p> 0.879) (Supplementary material 2). Both groups demonstrated comparable TF at IC. However, the healthy reference group demonstrated greater peak TF during landing compared to concussion history group on both dominant (healthy reference= 17.2 ± 8.5°, concussion history= 12.6 ± 7.2°, p= 0.031) and non-dominant limbs (healthy reference= 17.0 ± 7.7°, concussion history= 13.0 ± 7.1°, p= 0.023).

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 were observed between groups. Interestingly, the concussion history group displayed lower non-dominant limb peak pGRF compared to 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 post-concussion is reflected in knee biomechanical alterations during jump-landing tasks. Additionally, both groups displayed unfavorable knee biomechanics in more motor challenging conditions (single- vs. double-leg conditions); however, adding cognitive demands into 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 indicated that individuals with a recent concussion (average of 5.4 months) could demonstrate comparable landing strategies as their match controls when they were clinical recovered.

Jump-landing biomechanics comparison between groups

Previous studies have suggested that single-leg jump-landing tasks[11] 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 concussion history demonstrated smaller peak KF and greater peak KAB compared to 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 previous study[28] may be attributed to variations in jump-landing protocols (forward jump-landing on the dominant or non-dominant limb vs. jump-cutting tasks on the dominant limb only[28]), the timing of flanker figure presentation (6% of anterior displacement of front head marker vs. 0.5s prior to ground contact[28]), and sex distribution (85% vs 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 to the concussion history group. These findings suggested that 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,[26] suggesting that the healthy reference group might display lower pGRF than the concussion history group. 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 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,[29] indicating both groups displayed knee joint angles within the normative range. Additionally, McNair et al. (1999)[30] established normative values of vGRF during jump-landing tasks in adolescents (4.5 ± 1.7 %BW), and Heebner et al (2017)[31] reported knee biomechanics across 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, while the concussion history group demonstrated statistically significant lower non-dominant limb peak pGRF compared to healthy reference group (average of 5 %BW difference), this difference may not 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 non-dominant limb peak pGRF (R^2= 0.401, β= -0.633, p= 0.011). 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 indicated that the number of concussion history or concussion history affected GRF outcomes. Future research should include the number of prior concussions as a covariate and recruit 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 difference 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,[8,15] potentially resulting from neurophysiological alterations following concussion. A recent study found that college students with a history of concussion rely heavily on visual and vestibular feedback during postural control assessments compared to control groups.[32] The authors[32] 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. Our concussion history group may have utilized a similar compensatory mechanism during jump-landing tasks. However, without including visual or vestibular perturbations in 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 in 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 (e.g., 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 to condition without cognitive demands. These studies[31,33–35] suggest 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[34] incorporating cognitive demands into double-leg jump landing tasks, our study focus 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 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 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. While participants were recruited with a year of 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 non-dominant limbs. Future studies may consider including 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 age, sex, or activity level.

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 study 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 recovery timeline. This approach could offer clearer insights into the relationship between concussion history and jump-landing biomechanics.

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Legends to figures

Figure 1. Jump-landing task set-up and examples of visual target presentations including the "+" sign and arrow flanker figures

FP, Force plate

[a]For single-leg and single-leg with cognitive demands condition, the jump box was placed 25 % of participant's height away from the Force plate

[b]For double-leg condition, the jump box was placed 50 % of participant's height away from the Force plate

Figure 2. The group effect indicated that the peak pGRF of the non-dominant limb peak pGRF was lower for concussion history group compared to healthy reference group (concussion history= -0.62 ± 1.0 %BW, healthy reference= -0.67 ± 1.2 %BW, F1,50= 6.271, p= 0.016, η2= 0.111)

pGRF, posterior ground reaction force, DL: double-leg, SL: single-leg: SLF1: single-leg with flanker congruent, SLF2: single-leg with flanker incongruent

Table 1. Demographic information for healthy reference and concussion history group		
Demographics	Health reference group n= 26	Concussion history group n= 26
[a] Age, year	19.9 (1.3)	19.7 (1.2)
[b] Sex, female	22 (84.6)	22 (84.6)
[a] Height, cm	169.7 (8.8)	169.1 (9.0)
[a] Weight, kg	68.5 (10.2)	68.7(10.2)
[b] Dominant leg, right	25 (96.1)	25 (96.1)
[a] Tegner Scale	7 (2.2)	7 (2.0)
[b] Collegiate athletes	7 (26.9)	7 (26.9)
[b] Number of previous concussions		
1	-	11 (42.3)
2	-	8 (30.8)
3	-	7 (26.9)
[a] Time since most recent concussion, months	-	5.4 (3.2)
[a] Recovery time of most recent concussion, days	-	17.3 (13.4)

[a]Data presents as mean (SD)

[b]Data presents as number (%)

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

Recovery time of most recent concussion was calculated as the days between concussion and either receiving medical clearance or returning to pre-injury activity level

Table 2. Outcome measures associated with anterior cruciate ligament injury risk	
Sagittal plane variables	Frontal plane variables
[a] Knee flexion angle ↓	[a] Knee abduction angle ↑
[b] Peak Knee flexion angle ↓	[b] Peak knee abduction angle ↑
[a] Internal knee extension moment ↑	[a] Internal knee adduction moment ↑
[b] Peak internal knee extension moment ↑	[b] Peak internal knee adduction moment ↑
[b] Peak vertical ground reaction force ↑	
[b] Peak posterior ground reaction force ↑	

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

[a] Values at initial ground contact

[b] Peak values between initial ground contact and 100 milliseconds after initial ground contact

Table 3. Jump-landing outcomes between the groups. 3a: Double-leg condition, 3b: Single-leg condition, 3c: Single-leg arrow flanker congruent condition, 3d: Single-leg arrow flanker incongruent condition

Table 3a. Jump-landing outcomes during double-leg condition

	Healthy reference group n= 26		Concussion history group n= 26	
	Dominant	Non-dominant	Dominant	Non-dominant
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 x HT	-0.001 (0.017)	-0.003 (0.015)	-0.004 (0.015)	-0.010 (0.013)
KAM, % BW x HT	0.011 (0.008)	0.008 (0.007)	0.007 (0.008)	0.010 (0.007)
Peak[a]				
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 x HT	0.15 (0.02)	0.14 (0.02)	0.16 (0.03)	0.14 (0.03)
KAM, %BW x 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)

Data presents as mean (SD)

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

Positive values indicate extension and adduction angle/internal moment, as well as anterior ground reaction force

[a]Peak values between initial ground contact and 100 ms after initial ground contact

Table 3b. Jump-landing outcomes during single-leg condition

	Healthy reference group n= 26		Concussion history group n= 26	
	Dominant	Non-dominant	Dominant	Non-dominant
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 x HT	-0.017 (0.012)	-0.012 (0.015)	-0.012 (0.010)	-0.014 (0.014)
KAM, % BW x HT	0.006 (0.007)	0.005 (0.006)	0.005 (0.005)	0.007 (0.006)
Peak[a]				
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 x HT	0.17 (0.02)	0.18 (0.02)	0.18 (0.03)	0.17 (0.03)
KAM, % BW x 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)

Data presents as mean (SD)

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

Positive values indicate extension and adduction angle/internal moment, as well as anterior ground reaction force

[a]Peak values between initial ground contact and 100 ms after initial ground contact

Table 3c. Jump-landing outcomes during single-leg arrow flanker congruent condition

	Healthy reference group n= 26		Concussion history group n= 26	
	Dominant	Non-dominant	Dominant	Non-dominant
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 x HT	-0.015 (0.014)	-0.010 (0.014)	-0.015 (0.011)	-0.015 (0.012)
KAM, % BW x HT	0.006 (0.007)	0.006 (0.006)	0.004 (0.007)	0.006 (0.006)
Peak[a]				
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 x HT	0.17 (0.03)	0.17 (0.02)	0.17 (0.03)	0.17 (0.02)
KAM, % BW x 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)

Data presents as mean (SD)

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

Positive values indicate extension and adduction angle/internal moment, as well as anterior ground reaction force

[a]Peak values between initial ground contact and 100 ms after initial ground contact

Table 3d. Jump-landing outcomes during single-leg flanker incongruent condition

	Healthy reference group n= 26		Concussion history group n= 26	
	Dominant	Non-dominant	Dominant	Non-dominant
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 x HT	-0.013 (0.014)	-0.013 (0.014)	-0.016 (0.011)	-0.015 (0.015)
KAM, % BW x HT	0.005 (0.008)	0.003 (0.006)	0.003 (0.005)	0.005 (0.006)
Peak[a]				
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 x HT	0.17 (0.03)	0.17 (0.02)	0.17 (0.03)	0.17 (0.02)
KAM, % BW x 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)

Data presents as mean (SD).

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

Positive values indicate extension and adduction angle/internal moment, as well as anterior ground reaction force

[a]Peak values between initial ground contact and 100 ms after initial ground contact

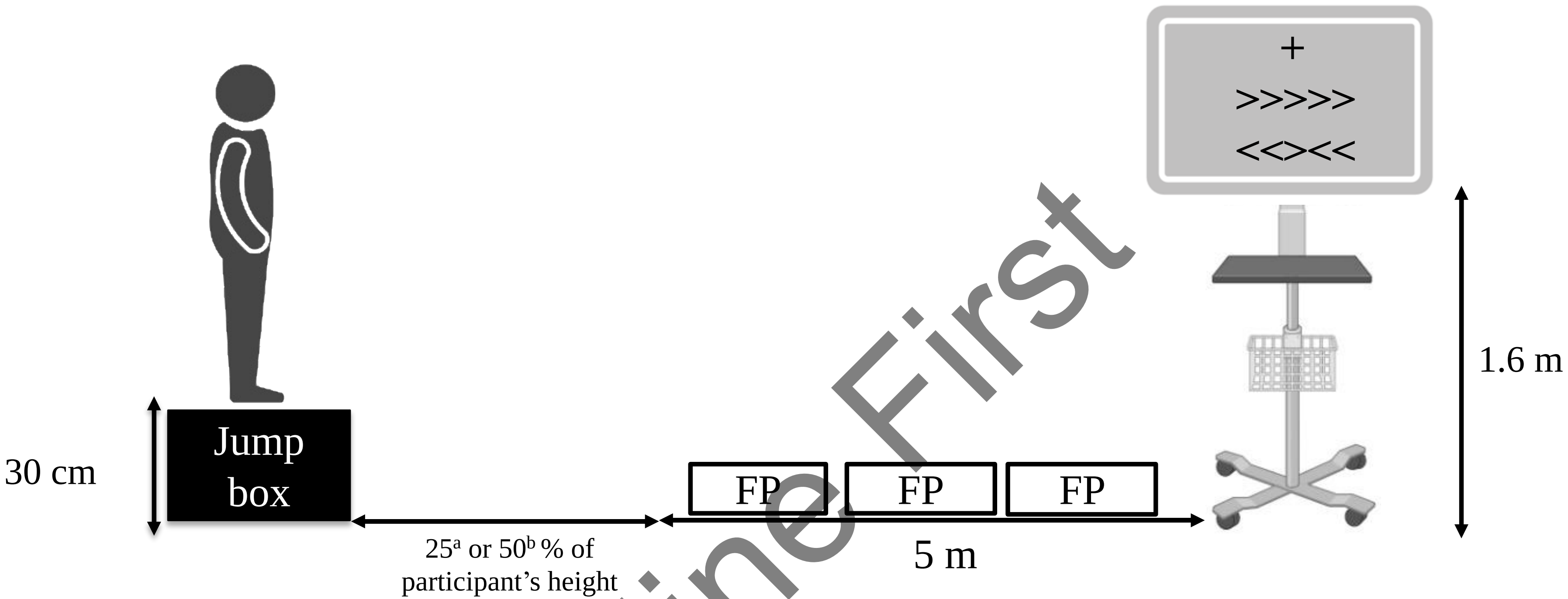

Figure 1. Jump-landing task set-up and examples of visual target presentations including the "+" sign and arrow flanker figures

FP, Force plate

[a]For single-leg and single-leg with cognitive demands condition, the jump box was placed 25 % of participant's height away from the Force plate

[b]For double-leg condition, the jump box was placed 50 % of participant's height away from the Force plate

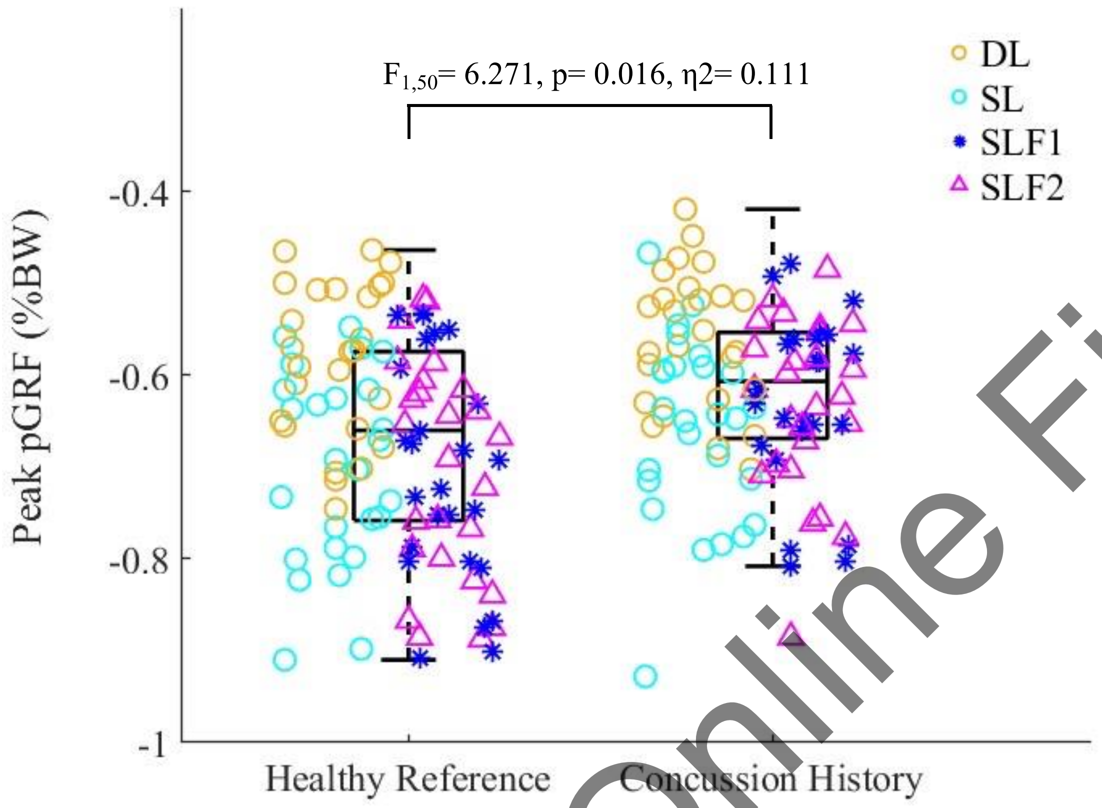

Figure 2. The group effect indicated that the peak pGRF of the non-dominant limb peak pGRF was lower for concussion history group compared to healthy reference group (concussion history= -0.62 ± 1.0 %BW, healthy reference= -0.67 ± 1.2 %BW, $F_{1,50}$= 6.271, p= 0.016, η2= 0.111)

pGRF, posterior ground reaction force, DL: double-leg, SL: single-leg: SLF1: single-leg with flanker congruent, SLF2: single-leg with flanker incongruent

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 1a. Interactions and main effects for four jump-landing outcomes on dominant legs between the groups

	Interaction effect			Task effect			Group effect		
Dominant	F (3,150)	p	η2	F (3,150)	p	η2	F (1,50)	p	η2
Initial ground contact									
Knee flexion angle	0.71	0.479	0.014	224.19	**<0.001**	0.818	0.057	0.812	0.001
Knee abduction angle	0.074	0.409	0.001	11.141	**<0.001**	0.182	0.172	0.68	0.003
Internal knee extension moment	1.565	0.21	0.03	17.028	**<0.001**	0.254	0.009	0.926	<0.001
Internal knee adduction moment	0.497	0.623	0.01	10.614	**<0.001**	0.175	2.625	0.111	0.05
Peak									
Knee flexion angle	1.21	0.297	0.024	844.63	**<0.001**	0.944	0.441	0.51	0.009
Knee abduction angle	0.448	0.572	0.009	45.583	**<0.001**	0.477	0.968	0.33	0.019
Internal knee extension moment	2.001	0.149	0.038	20.729	**<0.001**	0.293	0.648	0.425	0.013
Internal knee adduction moment	0.266	0.758	0.005	18.947	**<0.001**	0.275	0.394	0.533	0.008

Vertical ground reaction force	0.325	0.765	0.006	205.322	**<0.001**	0.804	3.351	0.073	0.053
Posterior ground reaction force	1.507	0.215	0.029	1.871	0.146	0.036	3.461	0.069	0.065

Bold area indicates $p < 0.05$

Supplementary material 1b. Interactions and main effects for four jump-landing outcomes on non-dominant legs between the groups

	Interaction effect			Task effect			Group effect		
Non-dominant	F (3,150)	p	η2	F (3,150)	p	η2	F (1,50)	p	η2
Initial ground contact									
Knee flexion angle	0.314	0.815	0.006	241.862	**<0.001**	0.829	0.608	0.439	0.012
Knee abduction angle	1.253	0.284	0.024	30.588	**<0.001**	0.380	0.018	0.895	<0.001
Internal knee extension moment	0.578	0.63	0.011	3.995	**0.009**	0.074	2.989	0.094	0.056
Internal knee adduction moment	0.517	0.944	0.002	13.555	**<0.001**	0.131	3.92	0.054	0.077
Peak									
Knee flexion angle	0.78	0.467	0.015	1116.27	**<0.001**	0.957	0.254	0.616	0.005
Knee abduction angle	0.089	0.619	0.01	30.287	**<0.001**	0.213	1.457	0.233	0.028

Internal knee extension moment	1.054	0.357	0.021	67.961	**<0.001**	0.576	0.006	0.938	<0.001
Internal knee adduction moment	0.613	0.54	0.012	23.383	**<0.001**	0.319	0.765	0.386	0.015
Vertical ground reaction force	1.187	0.317	0.023	214.466	**<0.001**	0.811	2.831	0.099	0.054
Posterior ground reaction force	1.610	.202	.031	25.145	**<.001**	0.335	6.271	**0.016**	0.111

Bold area indicates $p< 0.05$

Supplementary material 1c. Interactions and main effects for the symmetry of four jump-landing outcomes between the groups

	Interaction effect			Task effect			Group effect		
Symmetry	F (3,150)	p	η2	F (3,150)	p	η2	F (1,50)	p	η2
Initial ground contact									
Knee flexion angle	1.705	0.168	0.033	0.328	0.805	0.007	0.148	0.703	0.003
Knee abduction angle	0.130	0.863	0.003	1.911	0.157	0.037	0.532	0.469	0.011
Internal knee extension moment	0.126	0.944	0.003	0.883	0.451	0.017	2.503	0.120	0.048
Internal knee adduction moment	0.931	0.428	0.018	0.193	0.901	0.004	0.084	0.773	0.002
Peak									

Knee flexion angle	1.684	0.173	0.033	2.414	0.069	0.046	1.363	0.249	0.027
Knee abduction angle	0.591	0.562	0.012	2.672	0.072	0.051	1.446	0.235	0.028
Internal knee extension moment	0.536	0.627	0.011	2.151	0.108	0.041	0.467	0.498	0.009
Internal knee adduction moment	1.203	0.311	0.023	3.386	**0.020**	0.063	0.2627	0.111	0.050
Vertical ground reaction force	2.623	0.053	0.050	0.472	0.702	0.009	0.096	0.758	0.002
Posterior ground reaction force	1.282	0.283	0.025	1.127	0.331	0.022	1.583	0.214	0.031

Bold area indicates $p < 0.05$

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

Supplementary Material 2a. The cognitive accuracy for the single-Leg with cognitive demands condition

Arrow flanker (%)	Healthy reference group n= 26	Concussion history group n= 26	Group effect p
Right arrow			0.647
Congruent	100 (0)	97.9 (6.0)	
Incongruent	91.9 (11.9)	92.0 (15.0)	
Left arrow			0.297
Congruent	98.7 (4.0)	96.7 (10.2)	
Incongruent	90.6 (15.8)	87.2 (17.5)	

Data present as mean (SD)

2 groups x 2 conditions ANOVA with mixed design was conducted to compare the cognitive accuracy for the single-leg with cognitive demands condition between groups

Supplementary Material 2b. Movement initiation time for four jump-landing condition between groups			
Initiation time (s)	Healthy reference group n= 26	Concussion history group n= 26	Group effect p
Dominant			0.758
Double-leg	0.79 (0.16)	0.81 (0.08)	
Single-leg	0.79 (0.16)	0.79 (0.11)	
Single-leg + flanker congruent	0.73 (0.17)	0.75 (0.10)	
Single-leg + flanker incongruent	0.74 (0.15)	0.75 (0.09)	
Non-dominant			0.817
Double-leg	0.79 (0.16)	0.81 (0.08)	
Single-leg	0.86 (0.31)	0.78 (0.13)	
Single-leg + flanker congruent	0.74 (0.19)	0.74 (0.10)	
Single-leg + flanker incongruent	0.74 (0.17)	076 (0.10)	

Data present as mean (SD)

Movement initiation time was calculated as the time between the head and toe markers moving anteriorly by 2 standard deviations from their initial positions.

2 groups x 4 conditions ANOVA with mixed design was conducted to compare the movement initiation for between groups in 4 jump-landing conditions

Supplementary Material 2c. Jump-height for four jump-landing condition between groups

Jump height (cm)	Healthy reference group n= 26	Concussion history group n= 26	Group effect p
Dominant			0.758
Double-leg	14.5 (6.8)	13.7 (7.4)	
Single-leg	10.6 (6.1)	10.7 (5.1)	
Single-leg + flanker congruent	10.8 (6.9)	11.7 (5.4)	
Single-leg + flanker incongruent	10.9 (6.2)	11.5 (4.9)	
Non-dominant			0.879
Double-leg	14.5 (6.8)	13.7 (7.4)	
Single-leg	10.5 (5.1)	10.6 (6.0)	
Single-leg + flanker congruent	10.4 (6.4)	10.9 (5.5)	
Single-leg + flanker incongruent	10.6 (6.2)	11.4 (5.0)	

Data present as mean (SD)

Jump height was calculated as the vertical distance between the highest point and the initial position of the center of mass.

2 groups x 4 conditions ANOVA with mixed design was conducted to compare the jump-height between groups in 4 jump-landing conditions

s

Supplementary Material 2d. Trunk flexion angles four jump-landing condition between groups

	Healthy reference group n= 26		Concussion history group n= 26		Group effect p
	D	ND	D	ND	
Trunk flexion at IC, °					ND= 0.062 D= 0.060
Double-leg	15.0 (7.0)	15.0 (7.0)	11.6 (5.1)	11.6 (5.1)	
Single-leg	8.6 (7.9)	7.5 (6.0)	5.6 (5.7)	4.7 (5.2)	
Single-leg + flanker congruent	8.4 (6.9)	7.9 (7.0)	5.3 (6.1)	5.0 (6.2)	
Single-leg + flanker incongruent	8.1 (7.5)	8.0 (7.1)	4.7 (6.5)	5.4 (5.6)	
Peak Trunk flexion, °					ND= 0.031 D= 0.023
Double-leg	20.4 (7.5)	20.4 (7.5)	15.6 (6.1)	15.6 (6.1)	
Single-leg	16.8 (9.5)	15.9 (7.2)	13.0 (7.0)	12.1 (7.3)	
Single-leg + flanker congruent	15.9 (8.1)	15.7 (8.1)	11.5 (7.0)	12.1 (7.9)	
Single-leg + flanker incongruent	15.8 (8.6)	16.1 (7.4)	10.1 (7.9)	12.0 (7.4)	

Data present as mean (SD)

D, Dominant; ND, Non-Dominant

2 groups x 4 conditions ANOVA with mixed design was conducted to compare trunk flexion between groups in 4 jump-landing conditions