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ORIGINAL ARTICLE

The influence of concussion history and sex on lower extremity biomechanics during a cutting task

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ABSTRACT

The purpose of this study was to compare lower extremity biomechanics during a land-and-cut task between individuals with and without a sports related concussion (SRC) by sex. Twenty collegiate athletes with a history of SRC and twenty healthy college athlete controls performed an unanticipated land-and-cut task with both the dominant limb and the non-dominant limb. Reflective markers were placed on the spine, and bilaterally on the legs, thighs, and feet. Kinematic analyses from each reflective marker were captured using a ten camera Vicon motion capture system (240 Hz). Two force platforms (1200 Hz) were used for kinetic analyses. Vertical ground reaction force (vGRF), ankle dorsiflexion angle (DF), knee flexion angle (KFA), knee flexion moment (KFM), knee abduction angle (KAA), and knee abduction moment (KAM) were calculated during the first 100 ms after landing and compared between group and sex. Males in the SRC group landed with significantly less KFA compared to males in the control group. Males in the SRC group landed with a strategy conducive to increased lower extremity injury risk. Thus, concussion history of male athletes can contribute to their landing mechanics and should be taken into consideration during biomechanical assessments following a concussion.
Keywords: sports medicine; MTBI; landing; kinetics; kinematics; injury.

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INTRODUCTION

Sport-related concussions (SRCs) have recently received intense research focus due to their substantial fiscal impact on the US healthcare system, as well as their impact on the quality of life for athletes (Manley et al., 2017). Once an athlete sustains an SRC, stepwise return to play (RTP) protocols are implemented to ensure athletes are sufficiently prepared to resume sport. Current RTP criteria from an SRC involve a battery of clinical tests increasing in cognitive and exercise intensity (Broglio et al., 2014; Broglio et al., 2024; Patricios et al., 2023). Collegiate athletes typically pass standard RTP criteria for clearance to resume sport within 1-3 weeks post-injury (Broglio et al., 2014; Broglio et al., 2024; Patricios et al., 2023), however, long-term cognitive, neurophysiological, and motor impairments may still be present beyond this initial time period (Chmielewski et al., 2021; Howell et al., 2018). These impairments may lead to an increase in the likelihood for an athlete to sustain a musculoskeletal injury upon their return to sport. Recent findings suggest college athletes who have sustained an SRC are up to 3.7 times more likely to sustain a subsequent musculoskeletal injury compared to athletes without an SRC history (Broglio et al., 2014; Broglio et al., 2024; Patricios et al., 2023; Howell et al., 2018; Chmielewski et al., 2021; Brooks et al., 2016; Cross et al., 2016; Herman et al., 2016; Lynall et al., 2015; McPherson et al., 2018; Pietroscimone et al., 2015). Lower extremity (LE) musculoskeletal injuries are particularly common following an SRC (Herman et al., 2016; Pietroscimone et al., 2015). Athletes with an SRC history are almost 10% more likely to sustain a non-contact LE injury compared to healthy controls (Brooks et al., 2016). Non-contact LE injuries are of unique concern as they can often be directly attributed to motor control impairments. Although the exact link between SRC and LE injury is unknown, current literature suggests that athletes with a history of SRC perform high impact tasks (e.g., jump-landing and jump-cutting) with decreased LE neuromuscular control versus control athletes (Avedesian et al., 2020; Brooks et al., 2016; Dubose et al., 2017; Kowalczyk et al., 2024; Lapointe et al., 2018; Lee et al., 2021; Lynall et al., 2018; Shumski et al., 2024; Smulligan et al., 2022). Other possible contributions to increased injury risk include dysregulations to the vestibular system post-SRC, which can influence an athlete's ability to balance and maintain spatial orientation in athletic settings (Smulligan et al., 2022). Furthermore, from a cognitive perspective, athletes may exhibit impaired perception-action coupling ability post-SRC. This would lead to inadequate recognition of their action capabilities in relation to relevant situational or environmental information. Specifically, this could hinder an athlete's ability to make adequate movement decisions (action capabilities) specific to the environment around them, thus increasing injury risk based upon their movement behaviours (Eagle et al., 2019; Smulligan et al., 2022).

Although the noted impairments in neuromuscular control and cognition have been exhibited by many athletes post-SRC, these impairments have been shown to have a magnified effect in females. Female athletes who have sustained a SRC have demonstrated greater baseline concussion symptoms, greater reported symptom burden, longer recovery times, lower visual memory scores, and greater impairments in reaction time compared to male athletes who sustained an SRC (Covassin et al., 2006; Covassin et al., 2018; Frommer et al., 2011; Koerte et al., 2020). These impairments may secondarily contribute to increased injury risk upon sport resumption. However, research to support this claim and the influence of sex on injury risk in athletes with a concussion history is inconclusive. While previous literature has demonstrated the increased negative effects of SRC on female athletes, to our knowledge no study has compared LE landing biomechanics between males and females with a history of SRC. Comparing landing biomechanics between males and females with concussion history can provide greater insight as to the influence of sex on injury risk in these populations. More specifically, comparing LE biomechanics that have been previously linked to increased injury risk can give greater understanding as to which sex be at greater risk for LE injury. Therefore, the purpose of this study was to compare lower extremity biomechanics during a land-and-cut task between males and females with and without a history of SRC. It was hypothesized that there would be differences in

landing mechanics between sexes. Specifically, it was hypothesized that female athletes in the SRC history group would exhibit lower extremity biomechanics during landing that are conducive to increased injury risk.

MATERIALS AND METHODS

Study design

Testing of each athlete was completed in one laboratory session. A total of 40 collegiate athletes participated in this study, including 20 athletes in the history of SRC group and 20 athletes in the control group. Each athlete was medically cleared for full sport participation at the time of testing. Athletes in the history of SRC group sustained their injury while participating in a National Collegiate Athletic Association (NCAA) Division 1 sport during any year of their collegiate career. For the purpose of this study, an SRC was defined as an altered mental status induced by biomechanical forces resulting in a variety of clinically overt signs and symptoms (Harmon et al., 2013). A physician confirmed the SRC occurrence and diagnosis using the following criteria: 1) observed and / or reported mechanism of injury, and 2) the presence of at least one or more of the following: a) on-field signs (e.g., loss of consciousness, amnesia, disorientation/confusion, balance difficulties), b) symptoms (e.g., headache, nausea, dizziness), and/or c) any impairment on sideline assessments (e.g., Sport Concussion Assessment Tool) (Avedesian et al., 2020). Each athlete in the control group did not report a SRC during their collegiate athletic career and this was confirmed through medical records. To minimize variation in each group, each participant in the history of SRC group was matched to a participant in the control group by sport, position, sex, and age (±1 year). Participant demographics are included in Table 1. Athletes were excluded if they reported any LE injury or any visual, physiological, or neurological conditions that would limit them from completing the required tasks.

Table 1. Athlete characteristics by group.

Characteristic	SRC Group	Control Group
Age (y)	20.5 ± 1.28	19.75 ± 1.29
Height (m)	1.81 ± 0.10	1.82 ± 0.09
Mass (kg)	85.96 ± 25.42	82.08 ± 23.40
Time Since Previous SRC (days)	461 ± 263	N/A
Men's Football (n)	6	6
Women's Volleyball (n)	4	4
Men's Soccer (n)	3	3
Women's Soccer (n)	3	3
Women's Rowing (n)	2	2
Women's Field Hockey (n)	1	1
Women's Diving (n)	1	1

Procedures

Prior to data collection, this study was approved by the institutional review board at the host university. All participants provided written consent for their participation in the study. Each athlete was instructed to complete a questionnaire regarding their SRC history during their collegiate athletic career (number of diagnosed SRCs and the amount of time since their most recent SRC). Upon completion of the informed consent and the questionnaire, the research team familiarized the athlete with all biomechanical testing procedures.

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Biomechanical assessment

Each athlete that participated in the study completed the biomechanical assessment while wearing compression clothing and athletic footwear. Height (m) and mass (kg), as well as each participant's self-defined dominant limb for their respective sport, were recorded prior to testing. Retro-reflective markers were placed on each athlete's upper thoracic and lumbar spine, as well as bilaterally on the thigh, leg, and dorsal surface of each foot. Joint locations were identified during a static calibration trial with a stylus to digitize anatomical landmarks at the C7 spinous process, L5 spinous process, medial and lateral femoral condyles, medial and lateral malleoli, and bases of the second and fifth metatarsals (Avedesian et al., 2020).

Following the static calibration trial, each athlete performed a land-and-cut assessment. Athletes began the assessment standing on a 60cm box and faced a visual stimulus via a light disc (FITLIGHT Corp., Aurora, Ontario, CA) placed three meters in front of the landing apparatus. Each athlete was shown several different flashing colours (green, red, pink, and blue) on the light disc. Athletes were instructed to only respond to a final red or green light. If a red or green light was presented, athletes stepped off the box, landed on both feet, then performed a 45-degree cutting manoeuvre to the left (green light) or right (red light) as quickly as possible. The limb that performed each cutting manoeuvre was the limb of interest for analysing biomechanical variables. Each athlete was allowed up to four practice trials prior to data collection. Four trials for each limb were collected for data analysis and the average of these four trials was used for each biomechanical variable of interest.

Biomechanical data were collected with a 10-camera motion capture system (Vicon Motion Systems Ltd., Oxford, UK) sampled at 240 Hz and embedded force platforms (Advanced Medical Technology Inc., Watertown, MA, USA) sampled at 1200 Hz (Avedesian et al., 2020). For the land-and-cut manoeuvres to both sides, biomechanical dependent variables of interest included selected peak kinetic and peak kinematic parameters that have been prospectively associated with LE injury during high impact loading tasks (Avedesian et al., 2020; Dubose et al., 2017; Lapointe et al., 2018; Howell et al., 2018; Lynall et al., 2018; Lynall et al., 2020). Each kinetic and kinematic variable was assessed during the first 100ms of ground contact with the force platform, which coincides with the time that many landing-related LE injuries occur (Koga et al., 2010). Ground contact was defined as the point when the vertical ground reaction force value exceeded 20N on the force platform. Biomechanical computations were performed using the Motion Monitor software (Innovative Sports Training Inc., Chicago, USA), in which marker trajectory and force platform data were smoothed with a fourth-order, low-pass Butterworth filter at 10 Hz, respectively. Kinetic moment parameters were computed using inverse dynamics and normalized to each participant's height and mass (Avedesian et al., 2020).

Statistical analysis

A two-way ANOVA (sex x group) for each dependent variable of interest on each limb was used to compare between history of SRC and control groups, as well as males and females. The biomechanical variables of interest were variables linked to LE injury risk, including vertical ground reaction force (vGRF), knee flexion moment (KFM), knee abduction moment (KAM), ankle dorsiflexion angle (DF), knee flexion angle (KFA), and knee abduction angle (KAA). Significance was set at $\alpha = .05$, and a Bonferroni correction was applied to adjust for multiple ANOVA tests. Extreme high outlier values for each variable were identified in SPSS Version 27.0 (IBM) as any value greater than the 75th percentile (Quartile 3) + 3 times the interquartile range (IQR) [Quartile 3 value + 3IQR]. Extreme low outlier values for each variable were identified as any value lower than the 25th percentile (Quartile 1) – 3 times the IQR [Quartile 1 value – 3IQR]. If any extreme high and low outlier values were identified, they were excluded from this study.

RESULTS

Residual analysis was performed to test for the assumptions of the two-way ANOVA. Outliers were assessed by inspection of a boxplot, normality was assessed using Shapiro-Wilk's normality test for each cell of the design and homogeneity of variances was assessed by Levene's test. There were no outliers, residuals were normally distributed ($p > .05$) and there was homogeneity of variances ($p > .05$). The mean and standard deviation of dependent variables by SRC history group and by sex for the dominant and non-dominant limbs are given in Tables 2 and 3.

Table 2. Dominant limb dependent variable differences between groups.

Dependent variable	SRC (mean ± SD)	Control (mean ± SD)	Male (mean ± SD)	Female (mean ± SD)
Vertical Ground Reaction Force (N/kg)	2.6 ± .38	2.4 ± .07	2.6 ± .38	2.4 ± .34
Dorsiflexion Angle (degrees)	15.1 ± 7.18	17.4 ± 8.53	14.8 ± 7.50	17.5 ± 8.12
Knee Flexion Angle (degrees)	54.1 ± 8.43	60.2 ± 8.94	57.5 ± 9.31	56.89 ± 9.19
Knee Flexion Moment (Nm/kg)	1.9 ± .51	2.1 ± .69	2.0 ± .70	2.1 ± .57
Knee Abduction Angle (degrees)	7.3 ± 3.9	9.0 ± 5.26	6.1 ± 4.67	9.7 ± 4.08
Knee Abduction Moment (Nm/kg)	0.5 ± .27	0.5 ± .23	0.5 ± .32	0.5 ± .17

Table 3. Non-dominant limb dependent variable differences between groups.

Dependent variable	SRC (mean ± SD)	Control (mean ± SD)	Male (mean ± SD)	Female (mean ± SD)
Vertical Ground Reaction Force (N/kg)	2.5 ± .46	2.5 ± .32	2.6 ± .34	2.4 ± .42
Dorsiflexion Angle (degrees)	16.0 ± 8.00	16.3 ± 9.72	16.1 ± 7.28	18.2 ± 8.49
Knee Flexion Angle (degrees)	54.0 ± 8.71	60.3 ± 6.67	55.0 ± 9.54	58.9 ± 6.83
Knee Flexion Moment (Nm/kg)	2.1 ± .52	2.3 ± .66	2.1 ± .53	2.3 ± .65
Knee Abduction Angle (degrees)	6.9 ± 3.20	7.6 ± 4.20	6.0 ± 2.78	8.3 ± 4.11
Knee Abduction Moment (Nm/kg)	0.4 ± .27	0.4 ± .21	0.4 ± .23	0.4 ± .23

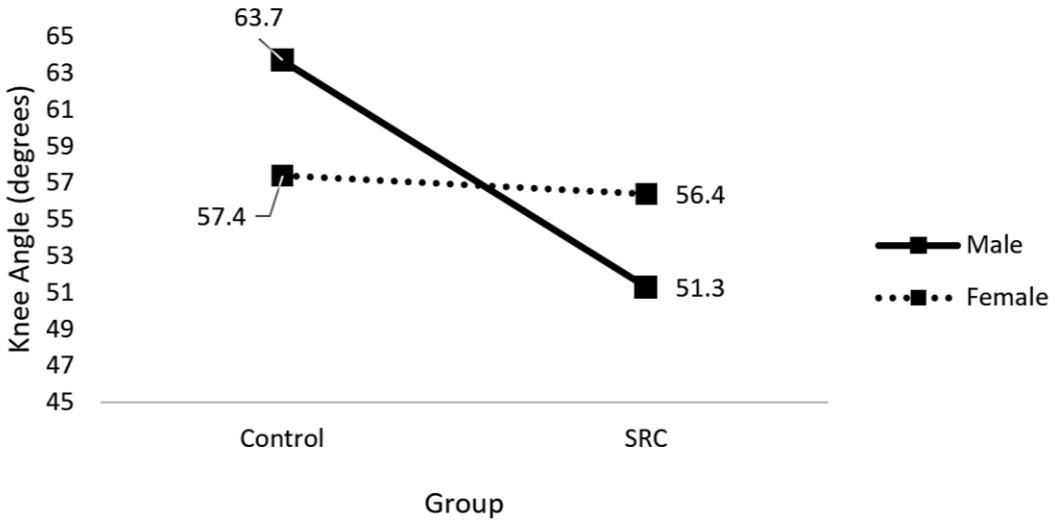

Figure 1. Dominant limb knee flexion angle.

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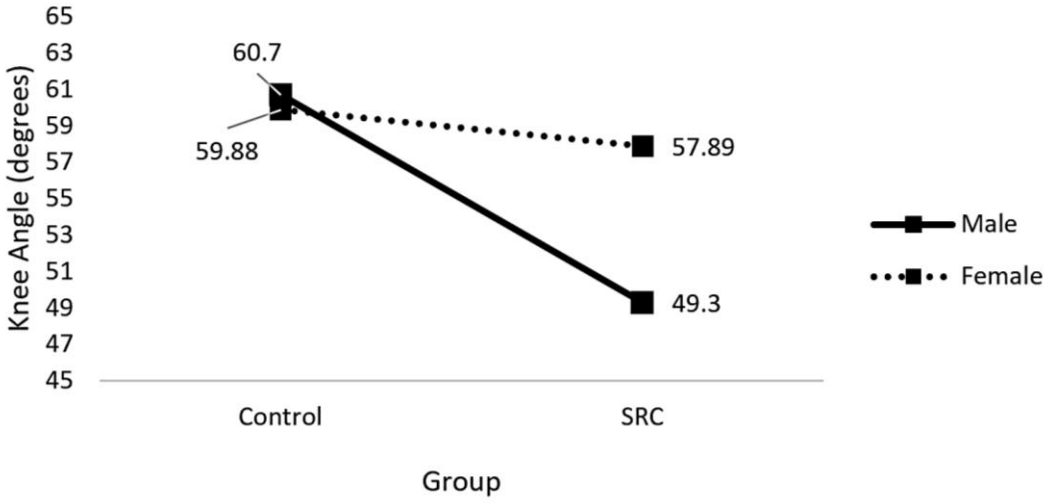

Figure 2. Non-dominant limb knee flexion angle.

There were no significant interactions between sex and history of SRC groups for vGRF, DF, KFM, KAA, or KAM on either limb ($p > .05$). A statistically significant sex x history of SRC group interaction was observed for dominant limb KFA, $F(1,36) = 4.56$, $p = .040$, partial $\eta 2 = .112$, and non-dominant limb KFA, $F(1,36) = 4.15$, $p = .049$, partial $\eta 2 = .103$. An independent-samples t-test showed that males in the history of SRC group ($M = 51.27$, $SD = 6.68$) demonstrated significantly lower dominant limb KFA than the healthy control group ($M = 63.71$, $SD = 7.24$), $t(16) = 3.787$, $p = .003$, $d = 1.79$, 95% CI [4.40, 20.47]. For the non-dominant limb KFA, independent-samples t-test results showed that males in the history of SRC group ($M = 49.28$, $SD = 8.35$) demonstrated significantly lower KFA than the healthy control group ($M = 60.72$, $SD = 7.08$), $t(16) = 3.134$, $p = .002$, $d = 1.48$, 95% CI [4.46, 18.41] (Figure 1 and Figure 2). p-values observed in the independent t-test accounted for the Bonferroni adjustment for multiple comparisons.

DISCUSSION

The purpose of this study was to compare lower extremity biomechanics during a land-and-cut task between males and females with and without a history of SRC. We hypothesized that there would be differences in LE landing biomechanics between sex. Specifically, we hypothesized that female athletes in the SRC history group would exhibit lower extremity biomechanics during landing that are conducive to increased injury risk. The results of our study partially supported our hypotheses. While there were differences in LE mechanics between sex, female athletes did not show any significant differences between history of SRC and control groups. A significant interaction showed that males in the history of SRC group demonstrated significantly less KFA in their dominant limb and non-dominant limb during the land-and-cut manoeuvre than males in the control group. Decreased KFA is indicative of a more upright landing posture that is characterized by lesser sagittal plane range of motion to attenuate the forces on the body, leading to increased injury risk, specifically anterior cruciate ligament (ACL) injury (Dufek & Bates, 1991). This is supported by in vivo and in vitro studies that demonstrated the highest amount of ACL strain during lesser knee flexion angles due to greater activation of the quadriceps causing anterior tibial translation (Demorat et al., 2004; Englander et al., 2019; Nasseri et al., 2020). Video analyses of non-contact ACL injuries occurring in sports have shown that the average KFA during ACL injuries to be between 11 degrees at initial contact to 61 degrees (Krosshaug et al., 2007). While females with and without a history of SRC had average KFAs within this range, the magnitude of KFA was nearly identical between them. Therefore, it cannot be concluded that females in the history of

SRC group demonstrated mechanics that were associated with greater risk for ACL injury any more than females in the control group. Males in the history of SRC group were within this range and demonstrated significantly less KFA than males in the healthy control group. Although not statistically significant, males in the history of SRC group also had lower KFA values than both female groups. Thus, it can be concluded that males in the SRC group adopted a strategy during landing that has been previously associated with greater risk for ACL injury. Results of this study contradict previous literature which stated that females tend to exhibit lower KFA during landing placing them at greater risk for ACL injuries (Chappell et al., 2007). The significant finding regarding KFA in this study supports other recent studies stating that neuromuscular deficits persist in athletes who have suffered an SRC even after standard RTP criteria have been cleared (Chmielewski et al., 2021; Howell et al., 2018). Lesser KFA during the land-and-cut manoeuvre may be attributed to a decrease in neuromuscular control (Eagle et al., 2019; Howell et al., 2018). This neuromuscular control deficit should be sufficiently addressed during concussion RTP protocols for athletes following an SRC to best reduce the likelihood of them sustaining a secondary injury upon their return to sport.

Several limitations should be acknowledged for this study. While 100ms after ground contact is the time period in which many lower extremity landing injuries occur, only examining this window may overlook important lower extremity mechanics that occur after. Although it may not be consistent with the timeframe of most lower extremity injuries related to landing, there may be meaningful or significant biomechanical adaptations that were not detected in our analysis. With our significant findings, the cross-sectional nature of this study did not allow us to examine whether the differences in KFA observed during this study existed prior to the athletes suffering their SRC. Thus, it cannot be concluded that the LE mechanics demonstrated by the athletes was caused by an SRC. The results of this study coincide with current literature stating that athletes with a history of SRC demonstrate decreased neuromuscular control during dynamic high impact movement tasks (Avedesian et al., 2020; Dubose et al., 2017; Lapointe et al., 2018; Lee et al., 2021; Lynall et al., 2018; Lynall et al., 2020). While the results of this study partially supported our hypothesis, it is possible that the male athletes already exhibited decreased KFA prior to their concussion. Thus, this cross-sectional study design does not allow us to truly conclude that the differences in KFA were fully attributed to SRC history. While the change in KFA indicates the possibility of decreased neuromuscular control, the non-significant findings in the other dependent variables of interest suggest that LE landing mechanics were mostly similar among males and females with and without SRC history. Thus, it is possible that the difference observed in KFA during landing may represent natural movement variability between athletes rather than post-SRC neuromuscular deficits. The lack of significant findings may also be attributed to the amount of time since the athletes sustained their SRC. The average time since the most recent SRC was 461 days, which may have limited the influence of SRC history on landing mechanics. This timeframe post-SRC indicates that, on average, athletes participated in this study long after their clinical recovery. Therefore, the negative impacts of SRC on neuromuscular control may have dissipated or been minimized at the time of participation in this study. Future studies should seek to recruit athletes in a shorter timeframe post-SRC or should group athletes according to their recovery time post-SRC. Another explanation for the predominance of null findings may lie in our sample size of 20 athletes in both the history of SRC and the control groups being further stratified by sex. The small sample size in each group may have influenced the limited significant findings of this study and increased the possibility of Type II error. Furthermore, data on subsequent LE injuries sustained following the athletes' SRC was not collected and thus we cannot assume that the differences observed in landing mechanics led to the athletes being injured. Our sample size in this study was solely limited to college athletes and thus generalizations to other age groups cannot be made. Furthermore, since SRC history prior to the athlete's collegiate career was not collected, it is possible that the number of SRCs was underrepresented.

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CONCLUSIONS

Evaluation of specific LE biomechanics during high impact landing tasks can have significant implications for injury risk. Although the significant findings were limited, our results suggested that the sex of the athlete can contribute to their landing mechanics and thus can be taken into consideration during jump landing biomechanical assessments. Implications of this study are applicable for athletic trainers, coaches, medical personnel, and other clinicians in the field of sports medicine to highlight the importance of implementing specific interventions to address potentially harmful landing mechanics in athletes who have suffered an SRC. Pertaining to RTP protocols following an SRC, analysing specific biomechanics during landing tasks is not currently considered. Practitioners should consider incorporating an unanticipated jump landing test as part of the RTP protocol. Currently, a single- and dual-task gait test is recommended (Patricios et al., 2023). Adding in an unanticipated jump test would allow for progression from a simple symptom-limited daily activity with an added cognitive demand (dual-task gait test) to a more dynamic, high-intensity, sports-specific activity with an added cognitive demand (unanticipated jump landing test). During the jump landing test, in addition to monitoring symptom exacerbation as a guide for progression, clinicians should assess and correct lower extremity biomechanics that are associated with increased injury risk. Assessing lower extremity biomechanics during RTP rehabilitation from a SRC can lessen the likelihood of athletes experiencing an LE injury upon their return to their sport.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualisation: Janet Dufek, Jason Avedesian, Tracey Covassin. Methodology: Janet Dufek, Jason Avedesian, Tracey Covassin. Formal analysis: Janet Dufek, Jason Avedesian, Tracey Covassin. Investigation: Janet Dufek, Jason Avedesian, Tracey Covassin. Data curation: Warren Forbes, Janet Dufek, Jason Avedesian, Tracey Covassin. Writing – original draft: Warren Forbes. Writing – review & editing: Warren Forbes and Janet Dufek. Supervision: Janet Dufek.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and

readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

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