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Research Article

The Influence of Concussion History and Sex on Limb Asymmetry During a Cutting Task

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Abstract

Introduction: Athletes with a concussion history are at increased risk for lower extremity injury compared to healthy athletes. Limb asymmetry during landing may be a factor that contributes to this increased injury risk, however this is currently unknown. The purpose of this study was to determine the effect of concussion history on limb symmetry during a cutting task.

Methods: Athletes with a history of sports-related concussion and a healthy control group performed an unanticipated land and cut maneuver with both the dominant limb side as well as the non-dominant limb side. Kinematic analyses were captured using a 10 camera Vicon motion capture system. Two force platforms were used for kinetic analyses. Biomechanical analyses on the dominant and non-dominant limbs were conducted and a symmetry index value was obtained for each variable of interest. Symmetry index values were compared between groups. Additional analyses were conducted comparing symmetry index values between males and females.

Results: Females in the concussion history group exhibited greater asymmetry in vertical ground reaction force compared to females in the control group ($p < .05$).

Conclusion: Results suggest that female athletes with a concussion history may exhibit mechanics during cutting that can place them at increased risk of lower extremity injury.

Keywords: *Head Injury; Kinematics; Kinetics; Motion Analysis*

Abbreviations

SRC: Sports-Related Concussion; RTP: Return to Play; PCEI: Post-Concussion Excursion Index; SI: Symmetry Index; ACL: Anterior Cruciate Ligament; DL: Dominant Limb; NDL: Non-Dominant Limb; vGRF: Vertical Ground Reaction Force; KFM: Knee Flexion Moment; KAM: Knee Abduction Moment; DF: Dorsiflexion Angle; KFA: Knee Flexion Angle; KAA: Knee Abduction Angle; IQR: Interquartile Range

Introduction

An abundance of research has been conducted on the prevalence of concussions that occur during sporting activities, commonly referred to as sports-related concussion (SRC). Beyond the substantial fiscal impact that SRCs play on the United States healthcare system, SRCs may impact quality of life for athletes [1]. Once an athlete sustains an SRC, stepwise return to play (RTP) protocols are implemented to ensure athletes are sufficiently prepared to resume sport. While current RTP criteria from an SRC involve a battery of clinical tests increasing in cognitive and exercise intensity [2], subtle long-term deficits may go undetected [3].

Collegiate athletes typically pass standard RTP criteria for clearance to resume sport within 2-4 weeks post-injury [2,4]. However, long-term cognitive, neurophysiological, and motor impairments may persist beyond this initial time period [3,5]. Although these impairments 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 an 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 [6-9]. If cognitive impairments such as decreased reaction time persist into sport participation and influence on the female athlete's performance, then this can secondarily contribute to increased injury risk. Recent findings suggest collegiate athletes who have sustained a SRC are approximately two times more likely to sustain a subsequent non-contact lower extremity (LE) injury compared to non-concussed athletes [10]. 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 [11-14]. An additional neuromuscular control risk factor for LE injury post-SRC may include postural instability due to limb asymmetry during dynamic motor tasks. To account for this, clinical assessments such as the Post-Concussion Excursion Index (PCEI) have been established to quantify the magnitude of symmetry between limbs [15]. With the PCEI test, thigh, and leg excursion of each limb during single-leg stance is quantified to generate a limb symmetry index in athletes with SRC. With this index, athletes with a history of SRC exhibited a PCEI percentage less than 80%, indicating significant limb asymmetry during the single limb standing task [15].

While the PCEI assessment has shown that post-SRC athletes exhibit limb asymmetry during a stationary standing task, the magnitude of limb asymmetry during dynamic, high impact tasks in this athlete population is currently unknown. Previous indexes of limb symmetry have been established to assess injury risk, such as the symmetry index (SI) [16-18]. It is suggested that asymmetries greater than 10% indicate an increased risk of musculoskeletal injury [19,20]. The nature of the SI index allows clinicians and sports medicine professionals to gauge symmetry between limbs during high velocity dynamic tasks such as a jump-cutting task. Therefore, it is essential for practitioners to analyze high-risk biomechanics and compare values between limbs, especially in a population susceptible to LE injury such as athletes with a history of SRC. Previous literature examining limb asymmetry during high impact landing and cutting tasks have linked lower extremity asymmetry with increased risk of LE injury, particularly anterior cruciate ligament (ACL) injury [21,22]. As LE limb asymmetry has provided value in predicting future LE injury in collegiate athletes, further study is required to determine if this LE injury mechanism is applicable to athletes with a history of SRC. Therefore, the purpose of this study was to compare limb symmetry during a cutting task in athletes with a history of SRC compared to a healthy control group. Along with concussion history, the influence of sex on limb asymmetry was also examined. It was hypothesized that athletes in the SRC group would have greater asymmetry amongst biomechanical variables of interest between limbs compared to the control group. It was further hypothesized that females would have greater limb asymmetry compared to males.

Materials and Methods

Testing of each athlete was completed during one laboratory session. A total of 40 collegiate athletes (20 athletes in each the history of SRC and control groups) participated in this study. Each athlete was medically cleared for full participant in their sport 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 a traumatic brain injury caused by a direct blow to the head, neck, or body resulting in an impulsive force being transmitted to the brain that occurs in sports and exercise-related activities [4]. 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) [23]. All athletes 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 current or prior LE injury or any visual, physiological, or neurological conditions that would limit them from completing the required tasks.

	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

Table 1: *Athlete characteristics by group.*

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.

Each athlete 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 marker clusters 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 [23].

Following the static calibration trial, each athlete performed a cutting task. 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 colors (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, participants stepped off the box, landed on both feet, then performed a 45-degree cutting maneuver to the left (green light) or right (red light) as quickly as possible. The limb [dominant (DL) or non-dominant (NDL)] that performed each cutting maneuver was the limb of interest for analyzing 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 [24]. For the cutting maneuvers using the DL or NDL, biomechanical variables of interest included selected peak kinetic (vertical ground reaction force, knee flexion moment, knee abduction moment) and peak kinematic (ankle dorsiflexion, knee flexion, knee abduction angle) parameters that have been prospectively associated with LE injury during high impact loading tasks [3,11-14,24,25]. 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 [26]. 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 [23].

Limb symmetry during the cutting task was computed with the symmetry index (SI) defined as [16-18]:

SI = (High Score – Low Score)/Total ×100.

The high score was the kinematic or kinetic variable with the greater value and the low score was the kinematic or kinetic variable with the lower value between the DL and NDL limbs. For example, if the DL had a peak knee flexion angle of 90 degrees and the NDL had a peak knee flexion angle of 80 degrees, the SI would be 5.9%.

A two-way ANOVA (sex x group) for each SI dependent variable of interest was used to compare between history of SRC and control groups, as well as males and females. 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. The SI 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 $\alpha = .05$. 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]. Extreme high and low outlier values were excluded from this study. For the history of SRC group, SI values for DF, KFA, KAA, and KAM were excluded for one athlete, and SI values for KFM were excluded for two athletes as statistical outliers. In the control group, SI values for vGRF, KFM, and KAA were excluded for one athlete, and DF SI values were excluded for three athletes as statistical extreme outliers. Residuals were normally distributed ($p > .05$) and there was homogeneity of variances ($p > .05$).

Results

The mean and standard deviation of SI values between groups are given in table 2.

	SRC (SI % ± SD)	Control (SI % ± SD)	Male (SI % ± SD)	Female (SI % ± SD)
Vertical Ground Reaction Force (vGRF)	6.81 ± 6.28	4.56 ± 3.77	3.93 ± 2.68	5.91 ± 6.13
Dorsiflexion Angle (DF)	15.07 ± 13.89	13.47 ± 10.97	14.94 ± 12.15	12.58 ± 10.55
Knee Flexion Angle (KFA)	4.36 ± 2.88	5.63 ± 4.30	2.69 ± 1.95	6.05 ± 4.26
Knee Flexion Moment (KFM)	9.37 ± 5.09	8.10 ± 5.08	6.86 ± 5.09	9.87 ± 5.21
Knee Abduction Angle (KAA)	23.74 ± 15.56	24.85 ± 18.53	21.04 ± 15.15	24.71 ± 19.03
Knee Abduction Moment (KAM)	26.17 ± 17.98	37.09 ± 22.32	31.55 ± 23.08	30.12 ± 15.86

Table 2: *Symmetry index differences between groups.*

There were no significant interactions or main effects in the SI between groups for DF, KFA, KFM, KAA, or KAM ($p > .05$). A statistically significant sex x group interaction was observed for vGRF $F(1,35) = 4.367$, $p = .044$, partial $\eta 2 = .111$. An independent t-test used for main effect analysis revealed that for vGRF females in the history of concussion group had significantly greater SI than females in the control group ($p = .039$) (Figure 1).

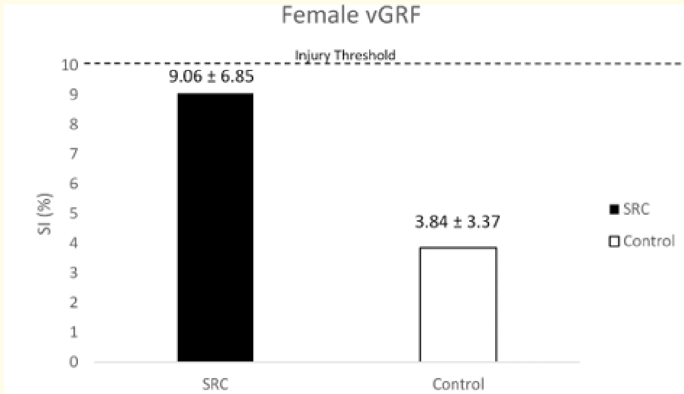

Figure 1: *Female vertical ground reaction force Symmetry Index percentage in SRC group compared to control group.*

Discussion

The purpose of this study was to compare limb symmetry during a cutting task in athletes with a history of SRC compared to a healthy control group. Additionally, this study aimed to assess the influence of sex on limb asymmetry. We hypothesized that the history of SRC group and females would exhibit greater SI among our biomechanical variables of interest compared to the control group and males, respectively. The results of this study partially supported our hypotheses. Although there were no significant main effect differences in SI between groups and sex for most biomechanical variables, there was a significant interaction for vGRF. Females in the history of SRC group had significantly greater SI for vGRF compared to females in the control group. A greater SI may indicate an increased risk for these female athletes to sustain a LE injury. Greater vGRF during landing and cutting has been associated with greater loads on the LE joints, particularly the knee joint. Higher vGRF during landing and cutting tasks increases the stress placed on the ACL and thus leads to greater risk for ACL related injuries [27,28]. Previous studies analyzing landing mechanics in male and female athletes have demonstrated that females tend to land with greater vGRF normalized to body weight compared to males, thus increasing their ACL injury risk [27]. Although this study did not directly examine the magnitude of vGRF during the cutting task, an increased SI indicates that the female athletes in the history of SRC group had greater vGRF in one limb compared to the other during the cutting task. A mean SI of 9.1% places these females directly below the established threshold of 10%, which is the maximum SI percentage recommended before LE injury drastically increases [19,20]. While the mean SI percentage for DF, KAA, and KAM exceeded this 10% threshold, the variability in SI between groups and sex was too high to detect any significant differences between groups. The high variability in SI also limits the applicability of these SI values to predict LE injury risk. To our knowledge, this study was the first to assess limb asymmetry during a cutting task in athletes with a history of SRC. Although not in the scope of the influence of SRC on LE injury risk, similar limb asymmetry results were observed by Paterno., *et al.* [29]. Limb asymmetry was analyzed during a drop jump task and compared between female athletes who had suffered an ACL injury versus controls. The group of female athletes who had sustained an ACL injury exhibited significantly greater differences in vGRF between limbs compared to the control group, thus potentially increasing their risk for subsequent ACL injury. The increase in the vGRF asymmetry in the group of female athletes who suffered an ACL injury in that study are comparable to the female athletes in this study who had a history of SRC.

Furthermore, the results of this study support previous literature stating that neuromuscular deficits persist in athletes who have suffered an SRC even after standard return to play (RTP) criteria have been met [3,30]. Greater limb asymmetry in females in the history of SRC group during a cutting task may be attributed to a decrease in neuromuscular control. This neuromuscular control deficit should adequately be addressed during the RTP protocols for athletes following their SRC to best reduce the likelihood of athletes sustaining an LE injury upon their return to their sport.

There were several limitations in this study that should be considered. The formula used for the SI allows for interpretation of the magnitude of asymmetry for each biomechanical variable between limbs but does not allow for interpretation of the directionality of asymmetry. The SI is unable to detect whether the asymmetry in vGRF is attributed to increased vGRF in the dominant limb compared to the non-dominant limb or vice versa. Other symmetry indices such as the limb symmetry index, bilateral asymmetry index, and the asymmetry index can account for specific directional differences between limbs (i.e., dominant/non-dominant or right/left). These indices are traditionally used to assess symmetry during bipedal hop tests where the limbs are functioning in conjunction with each other. For the cutting task used in this study, the limbs functioned independently and thus our focus was to analyze the overall magnitude of asymmetry as opposed to specific limb analyses. Another limitation was within our population of college athletes and their concussion history. For this study, the control group could not have any history of concussion while in their college athletic career. However, medical records prior to the athlete's collegiate career were not obtained and thus it is possible that they may have exhibited a concussion in high school. While they reported no concussion history, this was not confirmed through medical documentation. Additionally, the nature of this study did not allow us to examine whether these asymmetry differences in vGRF observed during this study existed prior to the athletes suffering their SRC. Lastly, while the difference observed in SI 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. This may be attributed to the amount of time since the athletes suffered their SRC. The average time post-SRC was 461 days which may have limited the influence of SRC history on landing mechanics. 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 [11,12,14,23-25]. While the results of this study support our hypothesis, it is possible that the athletes already exhibited asymmetry in vGRF prior to their concussion. Therefore, this cross-sectional study design does not allow us to truly conclude that the differences in asymmetry were fully attributed to their SRC history. Future studies should consider adopting a longitudinal approach that incorporates pre-season baseline testing in addition to a post-SRC assessment. This will allow researchers to more accurately assume causal relationship between SRC and lower extremity neuromuscular deficit.

Conclusion

Limb asymmetry during a cutting task may be a contributing factor to increase LE injury risk. However, analyzing asymmetry between limbs during high impact tasks such as a cutting maneuver is not currently considered in standard RTP protocols from an SRC. 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 targeted interventions to address limb asymmetry in athletes who have suffered an SRC. These targeted interventions during RTP rehabilitation from a SRC may reduce the likelihood of athletes suffering an LE injury upon their return to their sport.

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Conflict of Interest

The authors declare no conflicts of interest.

Bibliography

1. Manley Geoff., *et al*. "A systematic review of potential long-term effects of sport-related concussion". *British Journal of Sports Medicine* 51.12 (2017): 969-977.

2. Broglio Steven P., *et al*. "National Athletic Trainers' Association position statement: management of sport concussion". *Journal of Athletic Training* 49.2 (2014): 245-265.

3. Howell David R., *et al*. "Neuromuscular control deficits and the risk of subsequent injury after a concussion: a scoping review". *Sports Medicine (Auckland, N.Z.)* 48.5 (2018): 1097-1115.

4. Patricios Jon S., *et al*. "Consensus statement on concussion in sport: the 6th International Conference on Concussion in Sport-Amsterdam, October 2022". *British Journal of Sports Medicine* 57.11 (2023): 695-711.

5. Chmielewski Terese L., *et al*. "Impaired motor control after sport-related concussion could increase risk for musculoskeletal injury: Implications for clinical management and rehabilitation". *Journal of Sport and Health Science* 10.2 (2021): 154-161.

6. Covassin Tracey., *et al*. "Sex differences in sport-related concussion long-term outcomes". *International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology* 132.A (2018): 9-13.

7. Covassin T., *et al*. "Sex differences in baseline neuropsychological function and concussion symptoms of collegiate athletes". *British Journal of Sports Medicine* 40.11 (2006): 923-927.

8. Frommer Leah J., *et al*. "Sex differences in concussion symptoms of high school athletes". *Journal of Athletic Training* 46.1 (2011): 76-84.

9. Koerte Inga K., *et al*. "Sex-related differences in the effects of sports-related concussion: a review". *Journal of Neuroimaging: Official Journal of the American Society of Neuroimaging* 30.4 (2020): 387-409.

10. Lynall Robert C., *et al*. "Acute lower extremity injury rates increase after concussion in college athletes". *Medicine and Science in Sports and Exercise* 47.12 (2015): 2487-2492.

11. Dubose Dominique F., *et al*. "Lower extremity stiffness changes after concussion in collegiate football players". *Medicine and Science in Sports and Exercise* 49.1 (2017): 167-172.

12. Lapointe Andrew P., *et al*. "Kinematic differences during a jump cut maneuver between individuals with and without a concussion history". *International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology* 132.A (2018): 93-98.

13. Lynall Robert C., *et al*. "Single-legged hop and single-legged squat balance performance in recreational athletes with a history of concussion". *Journal of Athletic Training* 55.5 (2020): 488-493.

14. Lynall Robert C., *et al*. "Reaction time and joint kinematics during functional movement in recently concussed individuals". *Archives of Physical Medicine and Rehabilitation* 99.5 (2018): 880-886.

15. Feigenbaum Luis A., *et al*. "Post-concussive changes in balance and postural stability measured with CanesenseTM and the balance error scoring system (BESS) in division I collegiate football players: a case series". *International Journal of Sports Physical Therapy* 14.2 (2019): 296-307.

16. Bishop Chris., *et al*. "Asymmetries of the lower limb". *Strength and Conditioning Journal* 38.6 (2016): 33-43.

17. Sato Kimitake and Gary D Heise. "Influence of weight distribution asymmetry on the biomechanics of a barbell back squat". *Journal of Strength and Conditioning Research* 26.2 (2012): 342-349.

18. Shorter K Alex., *et al*. "A new approach to detecting asymmetries in gait". *Clinical Biomechanics (Bristol, Avon)* 23.4 (2008): 459-467.

19. Rohman Eric., *et al*. "Changes in involved and uninvolved limb function during rehabilitation after anterior cruciate ligament reconstruction: implications for Limb Symmetry Index measures". *The American Journal of Sports Medicine* 43.6 (2015): 1391-1398.

20. Zwolski Christin., *et al*. "The utility of limb symmetry indices in return-to-sport assessment in patients with bilateral anterior cruciate ligament reconstruction". *The American Journal of Sports Medicine* 44.8 (2016): 2030-2038.

21. Pfeiffer Steven J., *et al*. "Peak knee biomechanics and limb symmetry following unilateral anterior cruciate ligament reconstruction: Associations of walking gait and jump-landing outcomes". *Clinical Biomechanics (Bristol, Avon)* 53 (2018): 79-85.

22. Kyritsis Polyvios., *et al*. "Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture". *British Journal of Sports Medicine* 50.15 (2016): 946-951.

23. Avedesian Jason M., *et al*. "Landing biomechanics in adolescent athletes with and without a history of sports-related concussion". *Journal of applied biomechanics* 36.5 (2020): 313-318.

24. Avedesian Jason M., *et al*. "The influence of sports-related concussion on cognition and landing biomechanics in collegiate athletes". *Scandinavian Journal of Medicine and Science in Sports* 34.7 (2024): e14698.

25. Lee Bobby Jean., *et al*. "Movement patterns during a jump-landing task in athletes after sport-related concussion and healthy control individuals". *Journal of Athletic Training* 56.12 (2021): 1306-1312.

26. Koga Hideyuki., *et al*. "Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball". *The American Journal of Sports Medicine* 38.11 (2010): 2218-2225.

27. Hewett Timothy E., *et al*. "Understanding and preventing acl injuries: current biomechanical and epidemiologic considerations - update 2010". *North American Journal of Sports Physical Therapy: NAJSPT* 5.4 (2010): 234-251.

28. Leppänen Mari., *et al*. "Stiff landings are associated with increased ACL injury risk in young female basketball and floorball players". *The American Journal of Sports Medicine* 45.2 (2017): 386-393.

29. Paterno Mark V., *et al*. "Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction". *Clinical Journal of Sport Medicine: Official Journal of the Canadian Academy of Sport Medicine* 17.4 (2007): 258-262.

30. Eagle Shawn R., *et al*. "Increased risk of musculoskeletal injury following sport-related concussion: a perception-action coupling approach". *Sports Medicine (Auckland, N.Z.)* 50.1 (2020): 15-23.

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