Does prior concussion lead to biomechanical alterations associated with lateral ankle sprain and anterior cruciate ligament injury? A systematic review and meta-analysis

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ABSTRACT

Objective To determine whether individuals with a prior concussion exhibit biomechanical alterations in balance, gait and jump-landing tasks with and without cognitive demands that are associated with risk of lateral ankle sprain (LAS) and anterior cruciate ligament (ACL) injury.
Design Systematic review and meta-analysis.
Data sources Five electronic databases (Web of Science, Scopus, PubMed, SPORTDiscus and CiNAHL) were searched in April 2023.
Eligibility criteria Included studies involved (1) concussed participants, (2) outcome measures of spatiotemporal, kinematic or kinetic data and (3) a comparison or the data necessary to compare biomechanical variables between individuals with and without concussion history or before and after a concussion.
Results Twenty-seven studies were included involving 1544 participants (concussion group (n=757); non-concussion group (n=787)). Individuals with a recent concussion history (within 2 months) had decreased postural stability (g=0.34, 95% CI 0.20 to 0.49, p<0.001) and slower locomotion-related performance (g=0.26, 95% CI 0.11 to 0.41, p<0.001), both of which are associated with LAS injury risk. Furthermore, alterations in frontal plane kinetics (g=0.41, 95% CI 0.03 to 0.79, p=0.033) and sagittal plane kinematics (g=0.30, 95% CI 0.11 to 0.50, p=0.002) were observed in individuals approximately 2 years following concussion, both of which are associated with ACL injury risk. The moderator analyses indicated cognitive demands (ie, working memory, inhibitory control tasks) affected frontal plane kinematics (p=0.009), but not sagittal plane kinematics and locomotion-related performance, between the concussion and non-concussion groups.
Conclusion Following a recent concussion, individuals display decreased postural stability and slower locomotion-related performance, both of which are associated with LAS injury risk. Moreover, individuals within 2 years following a concussion also adopt a more erect landing posture with greater knee internal adduction moment, both of which are associated with ACL injury risk. While adding cognitive demands to jump-landing tasks affected frontal plane kinematics during landing, the altered movement patterns in locomotion and sagittal plane kinematics postconcussion persisted regardless of additional cognitive demands.
PROSPERO registration number CRD42021248916.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Gait alterations have been observed after returning to sport following a concussion.
⇒ Individuals may be more vulnerable to subsequent injury following concussion.

WHAT THIS STUDY ADDS

⇒ The decreased postural stability and locomotion-related performance following concussion are linked to an increased risk of lateral ankle sprain (LAS) injury.
⇒ Compared with individuals without a previous concussion, individuals with a concussion history display a more erect landing posture with similar sagittal plane internal joint loading during landing, and exhibit greater internal joint loading and comparable joint kinematics in the frontal plane, both of which are associated with anterior cruciate ligament (ACL) injury.
⇒ The addition of cognitive demands into jump-landing tasks following concussion increases frontal plane kinematics that could be linked to ACL injury risk.
⇒ The unfavourable locomotion-related performance and sagittal plane kinematics after a concussion persist regardless of the addition of cognitive demands in motor tasks.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Based on current findings, adding cognitive demands into jump-landing tasks is essential to identify the frontal plane biomechanical alteration associated with ACL injury risk; therefore, we recommend that clinicians include cognitive demands into motor function evaluations to inform decision-making of return-to-play following concussion.
⇒ To develop effective rehabilitative interventions, future research is warranted to investigate the underlying mechanism of biomechanical alterations following concussion that are associated with elevated LAS and ACL injury risks.

INTRODUCTION

Concussion is a major health concern to healthcare professionals worldwide. With an estimated global

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incidence of 600 cases per 100 000 people annually,[1] concussions present a significant financial burden on those seeking appropriate healthcare.[2] Emerging evidence has recognised an elevated risk of lower extremity musculoskeletal injury (LEMI) following concussion in high school,[3 4] collegiate[5–7] and professional athletes[8] after sport resumption, with 1.6 times higher LEMI incidence in athletes with a concussion history than in their non-concussed counterparts.[9] While the underlying mechanism for the elevated LEMI risk remains uncertain, previous research has suggested the full recovery of neuromuscular control following concussion[10–12] may extend beyond the clinically defined recovery period.[10 13] Insufficient recovery of neuromuscular control is then likely to predispose athletes to a greater injury risk on returning to competition.

The knee and ankle joints, along with ligamentous sprains and muscular strains, were the most commonly reported locations and types of injuries following a return to sport after concussion.[6 7] Recent evidence has suggested a greater odds of acute lateral ankle sprain (LAS) (OR=1.79)[6] and anterior cruciate ligament (ACL) (OR=1.6, 95% CI 1.1 to 2.4)[14] injury in individuals with a concussion history. Although there appears to be some commonality in connecting LEMI with a previous concussion, additional evidence is needed to identify the potential underlying mechanisms involved with these elevated risks.

Previous research has identified several biomechanical variables associated with locomotion[15 16] and jump-landing manoeuvres[17 18] that have helped to quantify neuromuscular control in individuals following concussion. Alterations in gait strategies have been observed during the acute phase (<3 days) and up to 2 months postinjury,[10 19 20] while aberrant jump-landing biomechanics have been identified[17 18 21] between individuals with and without a concussion history. Several other reports have indicated a task's cognitive requirements could affect one's ability to engage in dynamic activities involving walking[10] and jump-landing,[22 23] suggesting that cognitive demands could potentially moderate movement patterns. Determining movement pattern changes following concussion and identifying factors that influence these movement alterations could offer insights into an individuals' functional capacity and the associated subsequent injury risk during these activities.

Previous meta-analyses have identified specific biomechanical outcomes that are associated with sports injury[24 25]; however, a more comprehensive approach encompassing a pool of biomechanical outcomes associated with injury risk may better capture the multifactorial nature of sport injury. Such an approach could provide clinically meaningful information to healthcare professionals. Therefore, we conducted a systematic review and meta-analysis examining whether biomechanical alterations associated with LAS and ACL injuries are present following concussion. The secondary aim was to determine whether individuals with and without a previous concussion would exhibit biomechanical alterations related to these injuries when cognitive demands were added in motor tasks. We hypothesised that individuals with a concussion history would have decreased postural stability, compromised locomotion-related performance and deleterious landing biomechanics compared with those without a concussion history. Furthermore, we expected that cognitive demands would negatively impact the biomechanical alterations between individuals with and without a concussion history during dynamic activities.

METHOD

Protocol registration

This systematic review and meta-analysis was pre-registered at the International Prospective Register of Systematic Reviews.

Equity, diversity and inclusion statement

The author group comprises junior, mid-career and senior researchers from similar disciplines, with diverse cultural backgrounds. The included studies recruited male and female participants.

Data sources and search strategy

A two-step search strategy was used to identify literature examining the effect of concussion on biomechanical variables

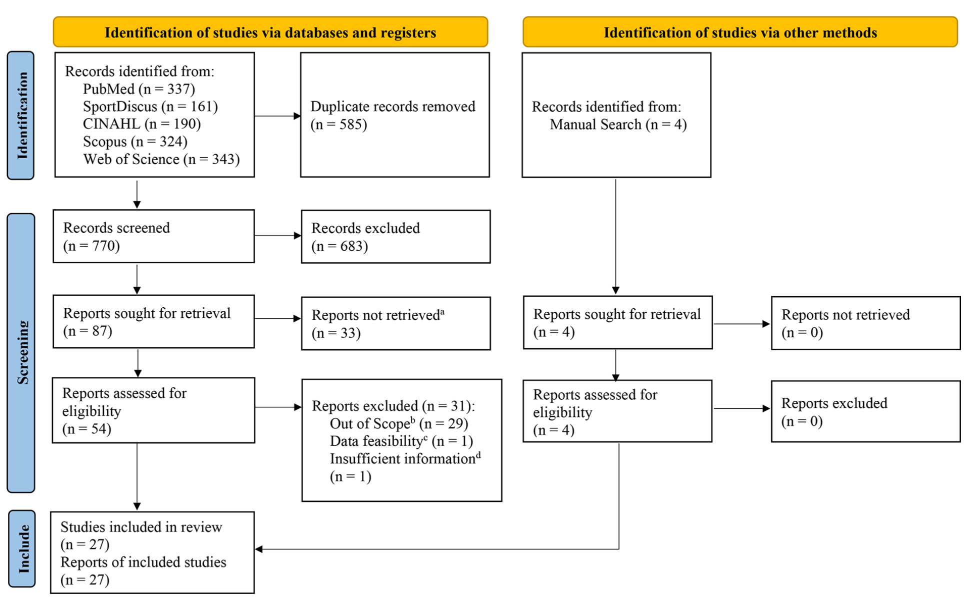

Figure 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses flowdiagram for study selection. [a]The full text of the manuscripts was not available. [b]We determined the biomechanical variables were not relevant to anterior cruciate ligament or lateral ankle sprain injury risk. [c]The effect size of the biomechanical outcomes was unable to compute with the included data. [d]The provided data was insufficient to make group comparisons for the study.

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related to LAS and ACL injuries. A methodical search of five databases, Web of Science, Scopus, PubMed, SPORTDiscus and CiNAHL, was conducted in April 2023. Key terms, including concussion, biomechanical measurement and study design, were used to identify relevant articles. Synonyms and common languages used within sports medicine and biomechanics were also included to fully identify all relevant literature related to the topics of interest. Each group of key terms was combined using the Boolean operator 'OR', and all groups of key terms were combined using the Boolean operator 'AND' into one search in each database. No limitations were imposed on the date of publication. Online supplemental appendix 1 highlights the specific key terms used in the search process. The second step included a *manual* search of additional articles not identified in the primary exploration.

Eligibility criteria

Studies were included if they met the following criteria: (1) participants included individuals with concussion, (2) measured outcomes using biomechanical variables (eg, walking speed, ground reaction force, joint angle, etc) and (3) provided a comparison or the necessary data to compare biomechanical variables between individuals with and without a concussion history, or before and after a concussion. Exclusion criteria involved: (1) biomechanical variables that are not related to LAS or ACL injury risk and (2) review articles, editorials, speeches, comments, abstracts, case studies, surgical procedures, non-peer-reviewed articles and articles not available in English.

Study selection

Two researchers (T-YC and Y-LH) independently reviewed the title and abstract for eligibility. Articles for which there was disagreement between the reviewers during the title and abstract review were included in the next, full-text review stage. The same two researchers independently reviewed the full text of the included articles, with the senior author (MFN) acting as the tiebreaker to resolve any disagreements. Cohen kappa coefficient (κ) and percent agreement served as the inter-rater agreement between the two reviewers. Interpretation of κ was based on Landis and Koch's criteria[26]: values less than 0 as no agreement, 0–0.20 as slight agreement, 0.21–0.40 as fair agreement, 0.41–0.60 as moderate agreement, 0.61–0.80 as substantial agreement and 0.81–1 as almost perfect agreement. Figure 1 outlines the study selection process.

Quality assessment

The National Institutes of Health (NIH) quality assessment tool for observational cohort and cross-sectional studies was used to assess the quality of the included studies.[27] Two researchers (T-YC and Y-LH) independently evaluated each study's quality. In instances of disagreement in rating, the two reviewers discussed disagreements until a consensus was reached.

Data extraction procedures

The authors used a standardised form to extract data from each study. The following data were extracted: (1) sample descriptors, including sample size, age, gender and health conditions, (2) concussion-related information, including the concussion definition, length of concussion and other related information, (3) biomechanical variables measured, including assessment methods and descriptive data, (4) methodological considerations, including statistical analyses, (5) standardised results involving mean, SD and p value along with effect size (F value, t value, standard difference in means) and (6) task conditions including both motor-only and motor with cognitive demands conditions. The extracted data from all included studies were then synthesised.

LAS and ACL construct determination

Two researchers (T-YC and Y-LH) evaluated the biomechanical variables in each included article and grouped them to form constructs related to LAS[25 28–34] or ACL[35] injuries. We operationally defined each construct as having the conceptual idea encompassing numerous elements with similar biomechanical features. The current study identified a total of eight constructs, with two associated with LAS injury risk (postural stability and locomotion-related performance) and six associated with ACL injury risk (frontal and sagittal plane kinetics and kinematics, impact loading, and trunk movements). For example, the frontal plane kinematics construct related to ACL injury included frontal plane joint position outcome variables that were previously reported to be associated with greater ACL injury risk, such as greater hip adduction and knee abduction angle. Two researchers with extensive lower-extremity biomechanics experience (MFN and CBC) evaluated the grouping of these biomechanical variables. Table 1 outlines the unfavourable directional effects (greater injury risk) of the biomechanical variables in each construct.

Table 1 The grouping of biomechanical variable in each construct

Lateral ankle sprain injury							
Postural stability	AP/ML COP length[25 28]↑	AP/ML COP amplitude[25 28]↑	COP velocity[25 28]↑	AP/ML root mean square sway[25 34]↑	Sway area[25 34]↑	Time to stabilisation[32 33]↑	95% ellipse sway area[25 34]↑
Locomotion	Gait/walking speed[29–31]↓	Time in double leg support[29–31]↑	Step length[29–31]↓	Cadence[30 31]↓			
Anterior cruciate ligament injury							
Frontal plane kinematics		Hip abduction[89]↓	Knee abduction[89]↑				
Frontal plane kinetics		Internal knee adduction[81 89]↑					
Sagittal plane kinematics		Hip flexion[80–82]↓	Knee flexion[80–82]↓	Ankle dorsiflexion[83 98]↓			
Sagittal plane kinetics		Internal hip extension[80 82]↑	Internal knee extension[80 82]↑				
Impact loading		vGRF[80–82]↑	Loading rate[90]↑				
Trunk mechanism		Trunk flexion[94 99]↓	Trunk lateral flexion[96 97 99]↑				

The arrows indicate the unfavourable direction of a given variable.
AP, anterior-posterior; COM, centre of mass; COP, centre of pressure; ML, medial-lateral; vGRF, vertical ground reaction force.

Statistical analysis

The statistical analysis results comparing biomechanical variables of concussed versus non-concussed participants were used as the effect size in the meta-analysis. Separate meta-analyses were conducted for each construct related to LAS and ACL injuries. To obtain a comprehensive comparison of the various biomechanical variables that were combined to form the constructs, we calculated and compared the overall differences by incorporating multiple unadjusted effect sizes from included studies. To avoid dependence on the effect sizes from the same study, effect sizes from the same study were averaged together based on the specific task conditions.[36] The summarised effect sizes for each construct were calculated by sample size, mean, SD, difference in means and p value. Hedges' g was used to report the effect size for each construct, considering the inclusion of various biomechanical variables. A random effects model was used in the meta-analysis based on the assumption that no one 'true' effect size across the included studies existed. Under the random effects model, individual study weights are assigned based on the study's effect size and variance that account for heterogeneity. To ensure the reliability of the synthesised results, a sensitivity analysis was performed for each construct by randomly removing one article at a time. Statistical heterogeneity was examined using the Cochran Q and I^2 index tests. The I^2 index is the proportion of the observed variability in effect among the included studies due to the true effect differences. An I^2 index between 0% and 20% represents low heterogeneity, 30% and 60% moderate heterogeneity, 50% and 90% substantial heterogeneity, and 75% and 100% considerable heterogeneity. Moderator analyses were conducted to identify the influence of cognitive demands on the relationship between biomechanical outcomes and concussion history. Cognitive demands were treated as categorical variables in the moderator analyses, and inclusion criteria required at least two separate effect sizes among the included studies.[36 37]

Risk of bias assessment

Publication bias was examined using funnel plots and the Egger's regression test. A visual inspection of symmetry within the funnel plot indicated that the included studies represented an unbiased range of effect sizes. Asymmetry in the funnel plot suggests publication bias toward a particular effect size or sample size. Egger's regression test was used to quantify bias using the effect sizes of each included study. For Egger's regression test, a p value *lower than* the alpha level of 0.05 indicates sufficient evidence of publication bias.[36]

RESULTS

Search results

The initial database search yielded 1355 articles. After removing duplicate items, 770 studies remained. Of these, 683 studies were removed after reviewing the title and abstract (percent agreement=85.4%, κ=0.39), and 87 were reserved for full-text review and eligibility assessment. Four additional studies were identified using manual search techniques during the full-text review. After careful scrutiny, 33 studies were excluded because full text were not available, and 31 studies were removed after it was determined the biomechanical variables were not relevant to ACL or LAS injury risk (n=29), the provided data was insufficient to make group comparisons (n=1) and the effect size of the biomechanical outcomes was not computable with the included data (n=1). Finally, 27 studies remained and were included in the meta-analysis (percent agreement=100%, κ=1) (figure 1).

Study characteristics

The total number of participants was 1544 (concussion group (n=757); non-concussion group (n=787)). The characteristics of the included studies are presented in online supplemental table 1. For the constructs related to LAS injury, the postural stability[38–46] and locomotion-related performance[39 46–57] constructs included 9 and 13 studies. For the constructs related to ACL injury, a total of four and five studies, respectively comprised the frontal plane kinetics[17 18 58 59] and kinematics[17 21 58–60] constructs. For sagittal plane kinetics[17 18 58 59 61] and kinematics[17 18 21 58–61] constructs, five and seven studies were identified, respectively; while three studies were included in the impact loading[17 58 59] and one study formed the ACL trunk mechanism[60] constructs.

The time frame between concussions incidence and the subsequent biomechanical evaluations associated with LAS and ACL injury constructs varied, ranging from 2 days to 34 months and 60 days following sport resumption to 6.5 years, respectively. For the constructs related to LAS injury, multiple studies observed deceased postural stability[38 39 42 44 46] and locomotion-related performance[39 49 50 54 56] in the concussion groups and these evaluations were performed within 2 months following concussion. In addition, for the constructs related to ACL injury, evidence indicated that individuals displayed altered biomechanical features during jump-landing were often assessed approximately 2 years postconcussion.[17 18 21 60 61]

Quality assessment

The results of the NIH quality assessment tool[27] indicated a range of reporting items from 5 to 9 (online supplemental appendix 2). Well-performed items encompassed stating the study objective, defining the study population, maintaining consistent participant recruitment, defining the exposure and using valid and reliable outcome measures. Conversely, determining the study sample size, implementing assessor blinding and providing justifications for confounding variables were the poorly performed items.

Publication bias

Publication bias was determined in the postural stability construct related to LAS (p=0.008). No publication biases were identified for the remaining constructs based on Egger's regression and the symmetry of the funnel plots (online supplemental appendix 3).

Heterogeneity

Table 2 includes the Cochrane Q and I^2 values for each construct. Heterogeneity was indictive in postural stability, locomotion-related performance and sagittal plane kinetics constructs.

Overall biomechanical presentations for each construct and moderator analysis

Online supplemental appendix 4 includes each construct's forest plots. Our findings revealed that those with a prior concussion had deceased postural stability during balance assessment (95% CI 0.20 to 0.49, p<0.001), reduced locomotion-related performance during walking (95% CI 0.11 to 0.41, p<0.001), landed with a more erect posture (95% CI 0.11 to 0.50, p=0.002) and greater internal knee adduction moment (95% CI 0.03 to 0.79, p=0.033) during jump-landing tasks. On the contrary, the concussion group exhibited frontal plane kinematics, sagittal plane kinetics, trunk movement and impact loading during jump-landing tasks that were comparable to the non-concussion group (table 2). Sensitivity analyses were performed for each construct, and the results remained consistent and unchanged.

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Table 2 Meta-analysis for each construct and moderator analysis for cognitive demands in locomotion, frontal and sagittal kinematic constructs

Construct	κ	Hedges' g	95% CI	P value	I2	Cochran's Q	df	P value
Ankle								
Postural stability	38	0.34	0.20 to 0.49	<0.001*	58.38	88.91	37	<0.001*
Locomotion	51	0.26	0.11 to 0.41	<0.001*	72.38	181.01	50	<0.001*
ACL								
Frontal plane kinetics	7	0.41	0.03 to 0.79	.033*	56.31	13.73	6	0.033
Frontal plane kinematics	12	−0.17	−0.41 to 0.08	0.177	26.55	14.98	11	0.184
Sagittal plane kinetics	8	−0.34	−0.96 to 0.29	0.289	84.09	43.99	7	<0.001*
Sagittal plane kinematics	16	0.30	0.11 to 0.50	.002*	20.39	18.84	15	0.221
Impact loading	5	0.21	−0.09 to 0.50	0.165	0	3.10	4	0.541
Trunk mechanism	5	0.31	−0.01 to 0.62	0.057	0	0.46	4	0.978
Moderator	**κ**	**Hedges' g**	**95% CI**	**I^2**	**Cochran's Q**	**df**	**P value**	
Locomotion				72.38	0.08	1	0.773	
Single task	29	0.30	0.07 to 0.54					
Dual task	22	0.26	0.14 to 0.39					
Frontal plane kinematics				26.55	6.79	1	.009*	
Single task	10	−0.06	−0.28 to 0.15					
Dual task	2	−0.97	−1.62 to −0.32					
Sagittal plane kinematics				20.39	1.05	1	0.305	
Single task	14	0.28	0.07 to 0.49					
Dual task	2	0.062	−0.003 to 1.25					

*p<0.05.
ACL, anterior cruciate ligament; df, degree of freedom; LAS, lateral ankle sprain.

In nine of the included studies, cognitive demands were added during motor examination.[21 39 46 47 49 50 52–54] Particularly, seven studies incorporated working memory tasks,[39 47 49 50 52–54] one study involved participants reading sports news[46] and one study included an inhibitory control task during motor tasks.[21] Three moderator analyses were completed in the locomotion-related performance, and frontal and sagittal plane kinematics constructs related to LAS and ACL injury. Our findings indicated when the cognitive demands were added in motor tasks, group differences were present in the frontal plane kinematics construct. Particularly, the concussion group displayed greater frontal plane kinematic alterations compared with the non-concussion group. However, the locomotion-related performance or sagittal plane kinematics constructs were similar between the groups (table 2).

DISCUSSION

The current study uses an innovative approach to incorporate and compare biomechanical variables with equivalent biomechanical features between individuals with and without a previous concussion. Our findings indicate that motor dysfunctions, including reduced postural stability, locomotion-related performance, and altered frontal and sagittal plane landing strategies, are present in those with concussion histories. Furthermore, no group differences were identified in the moderator analyses within the locomotion-related performance and sagittal plane kinematics constructs. Alternatively, groups differences were identified in the frontal plane kinematics construct when cognitive demands were considered. These findings indicated that alterations in frontal plane kinematics during jump-landing tasks may occur when cognitive demands are added, unlike locomotion-related performance and sagittal plane kinematics. Overall, individuals with a history of concussion may be more susceptible to either LAS and/or ACL injuries due to reduced postural stability, locomotion-related performance and landing in a more erect posture with greater internal knee adduction moment.

Postural stability related to LAS injury

Balance impairments are a well-known consequence of concussion and are routinely evaluated during concussion assessments.[62–64] An earlier meta-analysis identified balance alterations following concussion, highlighting a greater centre of pressure (COP) sway area was observed in individuals within 2 weeks of concussion.[65] Consistent with this notion, our results suggest that those with a concussion history display decreased postural stability, as inferred by higher COP velocity and COP length, when compared with non-concussed participants. Moreover, our study expands on previous findings[65] by including participants with various concussion history durations (ranging from 3 days to more than 12 months), suggesting the effects of concussion on balance control may be prolonged.

To maintain a homeostatic position, the visual, vestibular and proprioceptive systems must work harmoniously to generate proper muscle actions[54] and postural instability following concussion has been theorised to be the result of the inefficient integration of these three systems.[66 67] Impaired visual/oculomotor,[68] vestibular-ocular[69] and somatosensory[70] functions have been identified in individuals with concussion injury and impairments in the individual system may be further exacerbated by integrating information to initial motor movements, leading to balance problems. Slobounov *et al*[71] reported alterations in movement-related cortical potentials postconcussion, particularly the neural input from the prefrontal cortex into the supplementary motor cortex and abnormalities in the superior longitudinal fasciculi were observed, suggesting interference in the connections between brain regions.[72 73] These findings highlight that the brain networks responsible for organising and performing postural motions are disrupted following concussion, quite possibly leading to postural instability.

In a systematic review, McKeon and Hertel[74] concluded postural instability was associated with acute LAS. Similarly, following an acute LAS, prophylactic musculoskeletal exercise that incorporates balance training aids in reducing recurrent

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ankle sprain,[75] while balance training alone has shown to be effective in decreasing LAS incidence in athletes.[76] Therefore, postural instability is one of the factors to affect LAS risk. Given the frequent reports of balance problems postconcussion,[62–64] deficiency in balance control could be one of the factors contributing to the relationship between concussion and increased risk of LAS; however, more research is needed to investigate this relationship further.

Locomotion performance related to LAS injury

Studies have shown alterations in gait patterns occurring both acutely (<3 days) and up to 2 months postinjury in individuals with concussion compared with those without,[10 11 19] and these gait alterations were hypothesised to be a manifestation of neuromuscular dysfunction.[10 11] Gait speed, which is regulated by the basal ganglia receiving inputs from the motor cortex,[77 78] that have been suggested to be negatively affected by concussion.[79] Thus, the lingering gait alterations following concussion may result from an incomplete concussion recovery. Further research is necessary to investigate rehabilitative strategies for enhancing neuromuscular control recovery, facilitating a safer return to sports postconcussion. Büttner *et al*[19] conducted a meta-analysis and concluded that athletes who incurred a recent concussion walked slower than the healthy reference group during dual-task, but not single-task conditions. Our results align with those findings of Büttner *et al*[19] suggesting that concussion is associated with reduced locomotion-related performance, identified as slower gait speed, shorter step length and more time spent in double leg support during walking. However, our moderator analysis indicated that the addition of cognitive demands (single-task vs dual-task) does not affect the locomotion-related performance between the groups. The inconsistency in findings may be attributed to methodological differences between studies. Büttner *et al*[19] used individual participant data to analyse the included studies, whereas we adopted an innovative approach to include locomotion-related outcomes with similar biomechanical features. Additionally, Büttner *et al*[19] only included participants with *recent* concussion histories (2 months), while our study included participants with a wide-range of concussion histories. Nevertheless, it is important to note that despite the differences in methodological approaches and participant characteristics, both studies found consistent results regarding the association between concussion and reduced locomotion-related performance.

Sagittal plane kinetics and kinematics related to ACL injury

A recent study linked ACL injury to individuals with a concussion history.[14] Our results lend support to this finding[14] and revealed that the concussion group tended to land with an erect posture, including lesser hip, knee and/or ankle flexion (dorsiflexion), but experienced comparable sagittal plane internal joint moments during landing. Reduced hip, knee and ankle flexion and greater internal knee extension moment during landing have been linked to ACL injury risk.[80–83] Interestingly, under a given amount of quadriceps muscular contractions (internal knee extension moment)[84] or external force,[85] as the knee flexion decreases, the loading on the ACL increases. Such findings imply that ACL loading is likely greater during landings with reduced knee flexion but comparable internal knee extension moments. As such, the identification of this pattern of irregular sagittal plane landing biomechanics in the concussion group may provide a potential mechanism through which an individual's ACL injury risk is elevated postconcussion.

While the underlying mechanism of altered sagittal plane landing biomechanics is unknown, brain imaging and stimulation studies have revealed neurophysiological changes within the brain in individuals after a concussion, including the white matter abnormalities in internal capsule[73] and corpus callosum,[86] enhanced intracortical inhibition, and longer cortical silent period in the primary motor cortex.[79] These findings suggest that postconcussion neurophysiological irregularities in brain structures are related to motor control/planning and may alter functional movements. Additionally, a recent study has proposed athletes with acute concussions have a mild decrease in quadriceps muscular strength which could possibly be indicative of motor dysfunction following concussion.[87] Particularly, lower quadriceps muscular strength has been associated with lower knee flexion angle during the initial contact of jump-landing tasks.[88] Thus, deficits in quadriceps muscular strength could potentially affect sagittal plane jump-landing biomechanics and increase an individual's ACL injury risk. Collectively, it is plausible that those who have experienced concussions may have insufficient motor control/planning to perform adequate functional movements, yet further research is warranted to offer a more definitive answer.

Frontal plane kinetics and kinematics related to ACL injury

Interestingly, the results of the frontal plane construct diverge from those of the sagittal plane construct. These findings suggest that the concussion group experienced greater internal knee adduction moment compared with the non-concussion group but displayed similar frontal plane kinematics during landing. Greater knee abduction angle and greater internal knee adduction moment have been identified as predictors of ACL injury.[89] It has been postulated that insufficient neuromuscular control in the activation of the hamstrings and quadriceps muscles may serve as a potential mechanism, resulting in increased external knee abduction loading.[89] Neuromuscular dysfunction has been identified in individuals postconcussion[10 11] and athletes suffered from acute concussions may experience a slight decline in quadriceps muscular strength.[87] While the magnitude of the impact of quadriceps muscular strength deficits on internal knee adduction moment remains uncertain, it may be a potential manifestation of neuromuscular dysfunction following concussions.

Additionally, the moderator analysis indicated that cognitive demands affect frontal plane kinematics during landing in individuals with and without a history of concussion differently. The jump-landing condition may play a role in frontal plane demand during landing. Three included studies[21 59 60] used jump-cutting motions; however, only one determined that the concussion group had altered frontal plane kinematics when compared with the non-concussion group.[21] Lapointe *et al*[21] reported that those with a concussion history had higher peak knee valgus angles than those without concussion in both left and right cutting manoeuvres, when incorporating a cognitive challenge (arrow flanker task) during the jump-cutting motions. Accordingly, our moderator analysis suggests that cognitive demands affect the frontal plane joint angles between individuals with and without a concussion history. A combination of cognitive and motor task (dual-task) may be the key component to differentiate the frontal plane biomechanical alterations between individuals with and without a previous concussion; however, only one study[21] that incorporated cognitive challenges into jump-landing tasks was included in the current study, highlighting the need for additional research into this phenomenon.

Impact loading related to ACL injury

Regarding impact loading characteristics during jump-landing tasks, our findings do not support our hypothesis and suggest

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that those with concussion history experience equivalent lower extremity landing forces as those without concussion histories. In this review, we included three studies involving peak vertical ground reaction force (vGRF),[17 58 59] and vertical loading rate as outcome measures.[58] All of the included studies indicated that the concussion and non-concussion groups had comparable peak vGRF values and vertical loading rates during jump-landing tasks[17 58 59]; therefore, it is not surprising that our meta-analysis showed no group differences. It is reasonable to surmise those with and without a prior concussion experience similar loading force during jump-landing tasks.

The hazard of ACL injury has been linked to landing force disparities.[89] Research has determined that female adolescent athletes who experienced a future ACL rupture in their injured knee had 20% higher vGRF during the preseason baseline testing than their uninjured knee, as well as compared with female adolescent athletes who did not experience a future ACL injury.[89] Thus, avoiding greater landing forces during landing could be beneficial in decreasing the associated ACL injury risk following concussion. Other impact-related outcomes may be useful in distinguishing aberrant lower extremity impact loading between individuals with and without a history of concussion. Posterior ground reaction force[81] and landing force symmetry[90–92] have been implicated with increases in ACL injury risk; however, none of these biomechanical variables were included in the current review. Therefore, future research is needed to incorporate additional impact-related outcomes to further elucidate the lower extremity impact loading associated with ACL injury risk during landing in individuals following concussion.

Trunk mechanics related to ACL injury

Previous evidence has theorised that a more erect landing posture, defined by a more extended trunk, hip and knee position, is associated with ACL injury.[93] Additionally, studies have found trunk moment variations are related to changes in hip and knee kinetics and kinematics, which in turn impact ACL injury risk.[94–97] Our results contradict our hypothesis and suggest that those with a previous concussion have comparable trunk movements during landing than those without concussion histories. Although we observed a trend toward differences between the groups in the trunk movements, we caution that only one study[60] was included in this construct. Lynall *et al*[60] investigated different trunk kinematics during jump-landing tasks between individuals with and without a concussion history. Their study detected that the concussion group had a higher trunk flexion angle during an anticipated cutting motion as compared with the non-dominant side; however, the remaining jump-landing conditions were not statistically significant (double-leg, unanticipated cutting motion and anticipated cutting motion to dominant side).[60] Their findings suggest following concussion, trunk movements during landing may change and the movement alterations may be directionally dependent; however, only one study was included in the current review, so the clinical implications of the current finding are still inconclusive.

Limitations

The findings of the present study should be interpreted cautiously with the following limitations. While grouping various biomechanical outcomes under a construct allowed us to examine them collectively, it is plausible that certain outcomes within the construct may have a stronger influence on injury risk than others. Treating them equally may confound our interpretation. While we have conducted sensitivity analyses to ensure the robustness of our findings and provided fixed-effect model results (online supplemental appendix 5), the number of studies included and the sample sizes in the constructs related to ACL injury were limited and these studies predominantly used a cross-sectional design. Therefore, high-quality prospective studies are needed to better understand lower extremity biomechanics during functional movements following concussion. Various included studies employed diverse methodological approaches to address confounding factors between concussion and non-concussion groups. These approaches encompassed participant matching based on anthropometric information[18 21 38 40–42 45 46 48 49 51 55–61] and sports played,[41 46 49 59 61] as well as implementing covariates into statistical analysis[39 50 53] or using non-matching methods.[17 43 47 52 54] Thus, methodological differences should be taken into consideration when interpreting the present findings. Restricting the literature search to articles written in English may introduce potential selection bias, as relevant research published in other languages may be unidentified. However, due to language limitations, the author group was unable to comprehend articles written in languages other than English. Finally, the current study includes young (<25 years old) physically active participants or student-athletes. Therefore, our results may not be generalisable to other populations of different ages and physical activity levels.

CONCLUSION

The present study identified associations between concussion history and decreased postural stability and locomotion-related performance associated with LAS injury, and decreased sagittal plane kinematics and increased frontal plane kinetics linked to ACL injury. The addition of cognitive demands influences the frontal plane biomechanical presentations during landing. This study offers a foundation to enhance knowledge on subsequent injury risk after concussion.

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REFERENCES

1 Gardner RC, Yaffe K. Epidemiology of mild traumatic brain injury and neurodegenerative disease. *Mol Cell Neurosci* 2015;66:75–80.

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2 Pavlov V, Thompson-Leduc P, Zimmer L, *et al*. Mild traumatic brain injury in the united states: demographics, brain imaging procedures, health-care utilization and costs. *Brain Injury* 2019;33:1151–7.
3 Lynall RC, Mauntel TC, Pohlig RT, *et al*. Lower extremity musculoskeletal injury risk after concussion recovery in high school athletes. *J Athl Train* 2017;52:1028–34.
4 Biese KM, Kliethermes SA, Watson AM, *et al*. Musculoskeletal injuries and their association with previous concussion history: a prospective study of high school volleyball and soccer players. *Am J Sports Med* 2021;49:1634–41.
5 Brooks MA, Peterson K, Biese K, *et al*. Concussion increases odds of sustaining a lower extremity musculoskeletal injury after return to play among collegiate athletes. *Am J Sports Med* 2016;44:742–7.
6 Gilbert FC, Burdette GT, Joyner AB, *et al*. Association between concussion and lower extremity injuries in collegiate athletes. *Sports Health* 2016;8:561–7.
7 Fino PC, Becker LN, Fino NF, *et al*. Effects of recent concussion and injury history on instantaneous relative risk of lower extremity injury in division I collegiate athletes. *Clin J Sport Med* 2019;29:218–23.
8 Nordström A, Nordström P, Ekstrand J. Sports-related concussion increases the risk of subsequent injury by about 50% in elite male football players. *Br J Sports Med* 2014;48:1447–50.
9 McPherson AL, Nagai T, Webster KE, *et al*. Musculoskeletal injury risk after sport-related concussion: a systematic review and meta-analysis. *Am J Sports Med* 2019;47:1754–62.
10 Howell DR, Lynall RC, Buckley TA, *et al*. Neuromuscular control deficits and the risk of subsequent injury after a concussion: a scoping review. *Sports Med* 2018;48:1097–115.
11 Chmielewski TL, Tatman J, Suzuki S, *et al*. Impaired motor control after sport-related concussion could increase risk for musculoskeletal injury: implications for clinical management and rehabilitation. *J Sport Health Sci* 2021;10:154–61.
12 Wilkerson GB, Grooms DR, Acocello SN. Neuromechanical considerations for Postconcussion musculoskeletal injury risk management. *Curr Sports Med Rep* 2017;16:419–27.
13 Kamins J, Bigler E, Covassin T, *et al*. What is the physiological time to recovery after concussion? A systematic review. *Br J Sports Med* 2017;51:935–40.
14 McPherson AL, Shirley MB, Schilaty ND, *et al*. Effect of a concussion on anterior Cruciate ligament injury risk in a general population. *Sports Med* 2020;50:1203–10.
15 Howell DR, Buckley TA, Lynall RC, *et al*. Worsening dual-task gait costs after concussion and their association with subsequent sport-related injury. *J Neurotrauma* 2018;35:1630–6.
16 Oldham JR, Howell DR, Knight CA, *et al*. Gait performance is associated with subsequent lower extremity injury following concussion. *Med Sci Sports Exerc* 2020;52:2279–85.
17 Avedesian JM, Covassin T, Dufek JS. Landing biomechanics in adolescent athletes with and without a history of sports-related concussion. *J Appl Biomech* 2020:1–6.
18 Lee BJ, Blueitt D, Hannon J, *et al*. Movement patterns during a jump-landing task in athletes after sport-related concussion and healthy control individuals. *J Athl Train* 2021;56:1306–12.
19 Büttner F, Howell DR, Ardern CL, *et al*. Concussed athletes walk slower than non-concussed athletes during cognitive-motor dual-task assessments but not during single-task assessments 2 months after sports concussion: a systematic review and meta-analysis using individual participant data. *Br J Sports Med* 2020;54:94–101.
20 Buckley TA, Vallabhajosula S, Oldham JR, *et al*. Evidence of a conservative gait strategy in athletes with a history of concussions. *J Sport Health Sci* 2016;5:417–23.
21 Lapointe AP, Nolasco LA, Sosnowski A, *et al*. Kinematic differences during a jump cut maneuver between individuals with and without a concussion history. *Int J Psychophysiol* 2018;132:93–8.
22 Lempke LB, Oh J, Johnson RS, *et al*. Single- versus dual-task functional movement paradigms: a biomechanical analysis. *J Sport Rehabil* 2021;30:774–85.
23 McCarren G, Chaput M, Grooms DR, *et al*. Cognitive load influences drop jump landing mechanics during cognitive-motor-simulated shooting. *Mil Med* 2023:usad003.
24 Cronström A, Creaby MW, Ageberg E. Do knee abduction Kinematics and Kinetics predict future anterior Cruciate ligament injury risk? A systematic review and meta-analysis of prospective studies. *BMC Musculoskelet Disord* 2020;21:563.
25 Hiller CE, Nightingale EJ, Lin C-W, *et al*. Characteristics of people with recurrent ankle sprains: a systematic review with meta-analysis. *Br J Sports Med* 2011;45:660–72.
26 Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics* 1977;33:159.
27 National Institute of Health - National Heart Lung and Blood Institute. Quality assessment tool for observational cohort and cross-sectional studies. n.d. Available: https:// www.nhlbi.nih.gov/health-topics/study-qua
28 Yu P, Mei Q, Xiang L, *et al*. Differences in the locomotion biomechanics and dynamic postural control between individuals with chronic ankle instability and copers: a systematic review. *Sports Biomech* 2022;21:531–49.
29 Punt IM, Ziltener J-L, Laidet M, *et al*. Gait and physical impairments in patients with acute ankle sprains who did not receive physical therapy. *PM R* 2015;7:34–41.
30 Tenenbaum S, Chechik O, Bariteau J, *et al*. Gait abnormalities in patients with chronic ankle instability can improve following a non-invasive biomechanical therapy: a retrospective analysis. *J Phys Ther Sci* 2017;29:677–84.
31 Gigi R, Haim A, Luger E, *et al*. Deviations in gait metrics in patients with chronic ankle instability: a case control study. *J Foot Ankle Res* 2015;8:1.
32 Simpson JD, Stewart EM, Macias DM, *et al*. Individuals with chronic ankle instability exhibit dynamic postural stability deficits and altered unilateral landing biomechanics: a systematic review. *Phys Ther Sport* 2019;37:210–9.
33 Chan LYT, Sim YTN, Gan FK, *et al*. Effect of chronic ankle instability on lower extremity kinematics, dynamic postural stability, and muscle activity during unilateral jump-landing tasks: a systematic review and meta-analysis. *Phys Ther Sport* 2022;55:176–88.
34 Witchalls J, Blanch P, Waddington G, *et al*. Intrinsic functional deficits associated with increased risk of ankle injuries: a systematic review with meta-analysis. *Br J Sports Med* 2012;46:515–23.
35 Hewett TE, Ford KR, Hoogenboom BJ, *et al*. Understanding and preventing ACL injuries: current biomechanical and epidemiologic considerations - update 2010. *N Am J Sports Phys Ther* 2010;5:234–51.
36 Borenstein M, Hedges LV, Higgins JPT, *et al*. *Introduction to meta-analysis*. 2009.
37 Hak T, van Rhee H, Suurmond R. How to interpret results of meta-analysis. *SSRN Journal* 2016. 10.2139/ssrn.3241367 Available: https://www.ssrn.com/abstract=3241367
38 Baracks J, Casa DJ, Covassin T, *et al*. Acute sport-related concussion screening for collegiate athletes using an instrumented balance assessment. *J Athl Train* 2018;53:597–605.
39 Howell DR, Myer GD, Grooms D, *et al*. Examining motor tasks of differing complexity after concussion in adolescents. *Arch Phys Med Rehabil* 2019;100:613–9.
40 Lynall RC, Campbell KR, Mauntel TC, *et al*. Single-legged hop and single-legged squat balance performance in recreational athletes with a history of concussion. *J Athl Train* 2020;55:488–93.
41 Murray N, Belson E, Szekely B, *et al*. Baseline postural control and lower extremity injury incidence among those with a history of concussion. *J Athl Train* 2020;55:109–15.
42 Rochefort C, Walters-Stewart C, Aglipay M, *et al*. Balance markers in adolescents at 1 month postconcussion. *Orthop J Sports Med* 2017;5:2325967117695507.
43 Cochrane GD, Christy JB, Almutairi A, *et al*. Vestibular, oculomotor, and balance functions in children with and without concussion. *J Head Trauma Rehabil* 2021;36:264–73.
44 Hides JA, Franettovich Smith MM, Mendis MD, *et al*. A prospective investigation of changes in the sensorimotor system following sports concussion. *Musculoskelet Sci Pract* 2017;29:7–19.
45 King LA, Horak FB, Mancini M, *et al*. Instrumenting the balance error scoring system for use with patients reporting persistent balance problems after mild traumatic brain injury. *Arch Phys Med Rehabil* 2014;95:353–9.
46 Parrington L, Fino PC, Swanson CW, *et al*. Longitudinal assessment of balance and gait after concussion and return to play in collegiate athletes. *J Athl Train* 2019;54:429–38.
47 Solomito MJ, Kostyun RO, Wu Y-H, *et al*. Motion analysis evaluation of adolescent athletes during dual-task walking following a concussion: a multicenter study. *Gait Posture* 2018;64:260–5.
48 Stuart S, Parrington L, Morris R, *et al*. Gait measurement in chronic mild traumatic brain injury: a model approach. *Hum Mov Sci* 2020;69:102557.
49 Howell DR, Osternig LR, Chou L-S. Dual-task effect on gait balance control in adolescents with concussion. *Arch Phys Med Rehabil* 2013;94:1513–20.
50 Howell DR, Buckley TA, Berkstresser B, *et al*. Identification of post-concussion dual-task gait abnormalities using normative reference values. *J Appl Biomech* 2019;35:290–6.
51 Lynall RC, Blackburn JT, Guskiewicz KM, *et al*. Functional balance assessment in recreational college-aged individuals with a concussion history. *J Sci Med Sport* 2019;22:503–8.
52 Martini DN, Sabin MJ, DePesa SA, *et al*. The chronic effects of concussion on gait. *Arch Phys Med Rehabil* 2011;92:585–9.
53 Howell DR, Bonnette S, Diekfuss JA, *et al*. Youth with concussion have less adaptable gait patterns than their uninjured peers: implications for concussion management. *J Orthop Sports Phys Ther* 2020;50:438–46.
54 Howell DR, O'Brien MJ, Raghuram A, *et al*. Near point of convergence and gait deficits in adolescents after sport-related concussion. *Clin J Sport Med* 2018;28:262–7.
55 Pape MM, Kodosky PN, Hoover P. The community balance and mobility scale: detecting impairments in military service members with mild traumatic brain injury. *Mil Med* 2020;185:428–35.
56 Sambasivan K, Grilli L, Gagnon I. Balance and mobility in clinically recovered children and adolescents after a mild traumatic brain injury. *J Pediatr Rehabil Med* 2015;8:335–44.
57 Loyd BJ, Dibble LE, Weightman MM, *et al*. Volitional head movement deficits and alterations in gait speed following mild traumatic brain injury. *J Head Trauma Rehabil* 2023;38:E223–32.
58 Shumski EJ, Kasamatsu TM, Wilson KS, *et al*. Drop landing biomechanics in individuals with and without a concussion history. *J Appl Biomech* 2021;37:450–7.

Chou T-Y, *et al*. *Br J Sports Med* 2023;**57**:1509–1515. doi:10.1136/bjsports-2023-106980

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59 Avedesian JM, Covassin T, Baez S, *et al*. Relationship between cognitive performance and lower extremity biomechanics: implications for sports-related concussion. *Orthop J Sports Med* 2021;9:23259671211032246.
60 Lynall RC, Blackburn JT, Guskiewicz KM, *et al*. Reaction time and joint kinematics during functional movement in recently concussed individuals. *Arch Phys Med Rehabil* 2018;99:880–6.
61 Dubose DF, Herman DC, Jones DL, *et al*. Lower extremity stiffness changes after concussion in collegiate football players. *Med Sci Sports Exerc* 2017;49:167–72.
62 McCrory P, Meeuwisse W, Dvořák J, *et al*. Consensus statement on concussion in sport—the 5th international conference on concussion in sport held in Berlin, October 2016. *Br J Sports Med* 2017;51:838–47.
63 Echemendia RJ, Meeuwisse W, McCrory P, *et al*. The sport concussion assessment tool 5th edition (SCAT5): background and rationale. *Br J Sports Med* 2017;51:848–50.
64 Broglio SP, McCrea M, McAllister T, *et al*. A national study on the effects of concussion in collegiate athletes and US military service Academy members: the NCAA–DoD concussion assessment. *Sports Med* 2017;47:1437–51.
65 Wood TA, Hsieh KL, An R, *et al*. Balance and gait alterations observed more than 2 weeks after concussion: a systematic review and meta-analysis. *Am J Phys Med Rehabil* 2019;98:566–76.
66 Guskiewicz KM, Ross SE, Marshall SW. Postural stability and neuropsychological deficits after concussion in collegiate athletes. *J Athl Train* 2001;36:263–73.
67 Guskiewicz KM. Postural stability assessment following concussion: one piece of the puzzle. *Clin J Sport Med* 2001;11:182–9.
68 Santo AL, Race ML, Teel EF. Near point of convergence deficits and treatment following concussion: a systematic review. *J Sport Rehabil* 2020;29:1179–93.
69 Mucha A, Collins MW, Elbin RJ, *et al*. A brief vestibular/ocular motor screening (VOMS) assessment to evaluate concussions: preliminary findings. *Am J Sports Med* 2014;42:2479–86.
70 Lempke LB, Hoch MC, Call JA, *et al*. Lower extremity somatosensory function throughout concussion recovery: a prospective cohort study. *J Head Trauma Rehabil* 2023;38:E156–66.
71 Slobounov S, Sebastianelli W, Moss R. Alteration of posture-related cortical potentials in mild traumatic brain injury. *Neurosci Lett* 2005;383:251–5.
72 Chamard E, Lassonde M, Henry L, *et al*. Neurometabolic and microstructural alterations following a sports-related concussion in female athletes. *Brain Inj* 2013;27:1038–46.
73 Hellewell SC, Nguyen VPB, Jayasena RN, *et al*. Characteristic patterns of white matter tract injury in sport-related concussion: an image based meta-analysis. *Neuroimage Clin* 2020;26:102253.
74 McKeon PO, Hertel J. Systematic review of postural control and lateral ankle instability, part I: can deficits be detected with instrumented testing. *J Athl Train* 2008;43:293–304.
75 Bleakley CM, Taylor JB, Dischiavi SL, *et al*. Rehabilitation exercises reduce reinjury post ankle sprain, but the content and parameters of an optimal exercise program have yet to be established: a systematic review and meta-analysis. *Arch Phys Med Rehabil* 2019;100:1367–75.
76 Bellows R, Wong CK. The effect of bracing and balance training on ankle sprain incidence among athletes: a systematic review with meta-analysis. *Int J Sports Phys Ther* 2018;13:379–88.
77 Milardi D, Quartarone A, Bramanti A, *et al*. The Cortico-Basal Ganglia-Cerebellar network: past, present and future perspectives. *Front Syst Neurosci* 2019;13:61.
78 Caggiano V, Leiras R, Goñi-Erro H, *et al*. Midbrain circuits that set locomotor speed and gait selection. *Nature* 2018;553:455–60.
79 Tremblay S, de Beaumont L, Lassonde M, *et al*. Evidence for the specificity of Intracortical inhibitory dysfunction in asymptomatic concussed athletes. *J Neurotrauma* 2011;28:493–502.
80 Devita P, Skelly WA. Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Med Sci Sports Exerc* 1992;24:108–15.
81 Lin C-F, Liu H, Gros MT, *et al*. Biomechanical risk factors of non-contact ACL injuries: a stochastic biomechanical modeling study. *Journal of Sport and Health Science* 2012;1:36–42.
82 Trigsted SM, Post EG, Bell DR. Landing mechanics during single hop for distance in females following anterior cruciate ligament reconstruction compared to healthy controls. *Knee Surg Sports Traumatol Arthrosc* 2017;25:1395–402.
83 Padua DA, Marshall SW, Boling MC, *et al*. The landing error scoring system (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics: the jump-ACL study. *Am J Sports Med* 2009;37:1996–2002.
84 Li G, Zayontz S, Most E, *et al*. In situ forces of the anterior and posterior cruciate Ligaments in high knee flexion: an in vitro investigation. *J Orthop Res* 2004;22:293–7.
85 Sakane M, Fox RJ, Woo SLY, *et al*. In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. *J Orthop Res* 1997;15:285–93.
86 Chamard E, Lefebvre G, Lassonde M, *et al*. Long-term abnormalities in the corpus callosum of female concussed athletes. *J Neurotrauma* 2016;33:1220–6.
87 Chmielewski TL, Suzuki S, Dubose D, *et al*. Mild quadriceps and hamstring strength deficits do not persist after sport-related concussion. *Sports Health* 2023;15:512–8.
88 Nagai T, Sell TC, House AJ, *et al*. Knee proprioception and strength and landing kinematics during a single-leg stop-jump task. *J Athl Train* 2013;48:31–8.
89 Hewett TE, Myer GD, Ford KR, *et al*. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med* 2005;33:492–501.
90 Paterno MV, Ford KR, Myer GD, *et al*. Limb asymmetries in landing and jumping 2 years following anterior cruciate ligament reconstruction. *Clin J Sport Med* 2007;17:258–62.
91 Paterno MV, Schmitt LC, Ford KR, *et al*. Effects of sex on compensatory landing strategies upon return to sport after anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther* 2011;41:553–9.
92 Paterno MV, Schmitt LC, Ford KR, *et al*. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med* 2010;38:1968–78.
93 Griffin LY, Agel J, Albohm MJ, *et al*. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies. *J Am Acad Orthop Surg* 2000;8:141–50.
94 Blackburn JT, Padua DA. Influence of trunk flexion on hip and knee joint kinematics during a controlled drop landing. *Clin Biomech (Bristol, Avon)* 2008;23:313–9.
95 Blackburn JT, Padua DA. Sagittal-plane trunk position, landing forces, and quadriceps electromyographic activity. *J Athl Train* 2009;44:174–9.
96 Kristianslund E, Faul O, Bahr R, *et al*. Sidestep cutting technique and knee abduction loading: implications for ACL prevention exercises. *Br J Sports Med* 2014;48:779–83.
97 Jamison ST, Pan X, Chaudhari AMW. Knee moments during run-to-cut maneuvers are associated with lateral trunk positioning. *J Biomech* 2012;45:1881–5.
98 Boden BP, Torg JS, Knowles SB, *et al*. Video analysis of anterior cruciate ligament injury: abnormalities in hip and ankle kinematics. *Am J Sports Med* 2009;37:252–9.
99 Hewett TE, Torg JS, Boden BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *Br J Sports Med* 2009;43:417–22.

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