Journal of Athletic Training 2021;56(12):1306–1312
doi: 10.4085/533-20

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Movement Patterns During a Jump-Landing Task in Athletes After Sport-Related Concussion and Healthy Control Individuals

Bobby Jean Lee, DPT, PT*; Damond Blueitt, MD†; Joseph Hannon, PhD, PT, DPT*; Shiho Goto, PhD, ATC*; Craig Garrison, PhD, PT, ATC‡

*Texas Health Sports Medicine, Fort Worth; †Orthopedic Specialty Associates, Fort Worth, TX; ‡Ben Hogan Sports Medicine, Fort Worth, TX

Context: A relationship between a history of sport-related concussion (SRC) and lower extremity injury has been well established in the literature.

Objective: To determine if biomechanical differences existed during a double-limb jump landing between athletes who had been released to return to play after SRC and healthy matched control individuals.

Design: Cross-sectional study.

Setting: Health system–based outpatient sports medicine center.

Patients or Other Participants: A total of 21 participants with SRC (age = 15.38 ± 1.77 years, height = 169.23 ± 8.59 cm, mass = 63.43 ± 7.39 kg, time since release to return to sport after SRC = 16.33 ± 12.7 days) were compared with 21 age-, sex-, and activity-matched healthy participants serving as controls (age = 15.36 ± 1.73 years, height = 169.92 ± 11.1 cm, mass = 65.62 ± 12.08 kg).

Main Outcome Measure(s): Biomechanical performance during the double-limb jump landing was assessed using a motion-capture system and force plates. The average of 3 consecutive trials was used to calculate lower extremity joint kinetics and kinematics. The variables of interest were internal knee-extension moment, internal varus moment, and total sagittal-plane knee displacement for the dominant and nondominant limbs. Independent *t* tests were performed to examine the differences between SRC and control groups for the variables of interest.

Results: No differences existed between groups for the descriptive data. The SRC group demonstrated greater internal knee-extension moments in the dominant (–0.028 ± 0.009 Nm/kg, $P = .003$) and nondominant (–0.018 ± 0.007, $P = .02$) limbs. The SRC group also exhibited greater internal varus moments in the dominant (0.012 ± 0.004 Nm/kg, $P = .005$) and nondominant (0.010 ± 0.003, $P = .005$) limbs. For sagittal-plane knee displacement, the SRC group displayed less knee-flexion displacement in the dominant (–12.56 ± 4.67°, $P = .01$) but not the nondominant (–8.30 ± 4.91°, $P = .10$) limb.

Conclusions: Athletes who had been released for return to sport after SRC landed with greater knee valgus than healthy matched control participants.

Key Words: mild traumatic brain injuries, lower extremity injuries, biomechanics

Key Points

- Athletes who returned to play within 30 days of concussion moved differently than did healthy athletes.
- Biomechanical differences found after concussion may help to explain the identified relationship between concussion and lower extremity injuries.
- The mechanisms underlying these differences in biomechanical movement patterns are still unknown.

Sport-related concussion (SRC) is one of the most frequently reported sport-related injuries. The Centers for Disease Control and Prevention stated that in the United States alone, up to 3.8 million sports and recreational concussions occur each year.[1] Sport-related concussion is prevalent in many sports in the United States that rely heavily on the lower extremity (LE), such as football (6%),[2] soccer (11.1%),[3] and lacrosse (8.6%).[4] It is a multivariate diagnosis with various presentation patterns that make the diagnosis, treatment, and prognosis particularly challenging for health care providers. The current standard for determining readiness to return to play (RTP) is the use of a battery of tests in conjunction with a successful progression through an established RTP progression under the guidance of a licensed health care provider.[5] However, research[6–11] indicated that underlying deficits may persist after symptom resolution in SRC.

One such area of research is the emerging relationship between SRC and LE injuries. Regarding the LE injury risk, athletes with a history of concussion (either reported or unreported) had an increased risk of LE injury (odds ratio = 1.6–2.9 times).[12] This relationship has been found with strains, sprains, and ruptured ligament injuries of the knee, ankle, and foot.[13] The increased risk of LE injury after concussion was still present when a history of previous LE injury was controlled.[14] Investigators have

Table 1. Patient Characteristics

Characteristic	Sport-Related Concussion (n = 21)	Healthy Control (n = 21)	P Value
	Mean ± SD		
Age, y	15.38 ± 1.77	15.36 ± 1.73	.97
Height, cm	169.23 ± 8.59	169.92 ± 11.1	.83
Mass, kg	63.43 ± 7.39	65.62 ± 12.08	.51
Time spent in sport, h/wk	11.35 ± 6.02	10.13 ± 6.69	.76
	No.		
Sex, males/females	6/15	6/15	>.99
Single sport vs multisport	16 to 5	13 to 8	.32

suggested that a window of susceptibility to LE injury may exist after SRC. The overall increased risk of LE injury in athletes within 90 days of SRC was 2.48 times greater than that in healthy individuals[15] and decreased to 2.02 and 1.97 times within 180 and 365 days, respectively.[16]

Most authors studying the relationship between LE injuries and concussion have focused on collegiate and professional athletes. However, this trend has also been noted in younger athletes. In a population of >18 000 high-school–aged athletes, those with a history of concussion had odds of 1.34 of sustaining an LE injury that resulted in lost time.[17]

To date, the mechanism for this relationship has not been identified. Researchers[18] have proposed that a disruption in the perception-action coupling loop occurs after concussion and failure to reestablish this loop may increase the risk of subsequent injury. Another theory is that cerebellar dysfunction leads to disruption of afferent and efferent feedback loops that may result in the development of poor motor patterns and subsequent LE injury.[19] Other investigators[7,14,20] have examined differences in gait patterns under dual-task conditions between athletes who sustained and those who did not sustain a concussion. These studies suggested that the residual differences between healthy athletes and athletes who have sustained a concussion may be extrapolated and magnified during higher-level movements, such as running and cutting, while multitasking during sport participation, increasing the risk of injury.

Authors are beginning to characterize movement patterns that may increase the risk of LE injury using biomechanical analysis. Lapointe et al[19] observed that compared with healthy control individuals, athletes who presented 0.9 to 6.5 years after SRC (age range = 18–26 years) demonstrated increased knee valgus and internal rotation with a jump-cut maneuver. These biomechanical changes after SRC may contribute to the increased injury risk in this population.

To date, biomechanical analysis after SRC has primarily been conducted months to years from the time of RTP and in a more mature population, usually collegiate level or older. Limited information is available regarding the potential consequences and effects of SRC on LE movement patterns during the early stages of RTP in middle and high school–aged athletes. Therefore, the purpose of our study was to compare LE landing mechanics between adolescent athletes who were within 60 days of returning to sport after SRC and athletes without SRC (healthy control participants) during a double-limb jump-landing task. We hypothesized that athletes who were returning to play within 60 days after SRC would demonstrate altered LE biomechanics compared with the healthy control group during a jump-landing task.

METHODS

Participants

After screening, we enrolled 42 participants who met the inclusion criteria: 21 with an SRC (age = 15.38 ± 1.77 years, height = 169.23 ± 8.59 cm, mass = 63.43 ± 7.39 kg, time since release to RTP after SRC = 16.33 ± 12.7 days) and 21 healthy age-, sex-, and activity-matched control individuals (age = 15.36 ± 1.73 years, height = 169.92 ± 11.1 cm, mass = 65.62 ± 12.08 kg). Group characteristics are displayed in Table 1. For both groups, we considered recruits who were between the ages of 10 and 25 years, involved in a level 1 (eg, basketball, football or soccer) or level 2 (eg, baseball, softball) sport,[21] and not experiencing an active LE orthopaedic injury and who had not been injured in the 3 months before the study. In addition, to further ensure that our control group represented a healthy population, these athletes had no history of LE orthopaedic surgery (eg, anterior cruciate ligament reconstruction), and only those who achieved a score of ≥95 on the International Knee Documentation Committee Short Form were included. For the SRC group, we included participants if they had been diagnosed with an SRC, had been cleared to RTP, and completed testing within 60 days of beginning an RTP progression. We defined *RTP progression* as the symptom-dictated progression that may be prescribed, monitored, and individualized by the physician or athletic trainer and followed by athletes in order to return to sport after they were medically cleared. We tested participants with SRC within 60 days of being cleared to begin an RTP progression by the supervising physician. Healthy control participants were tested at various times throughout their seasons. All participants provided informed consent. If the participant was a minor, parental consent and participant assent were obtained. The Institutional Review Board of Texas Health Resources approved the research procedures.

Procedures

Instrumentation. Participants' performance of the jump-landing task was recorded using a 3-dimensional (3D) motion-capture system and 2 force plates. An 8-camera motion-capture system (Qualisys AB) with a sampling rate of 120 Hz captured joint motions in all 3 planes during the task. Thirty-three reflective markers were adhered to each

Figure 1. Marker placements.

participant's skin or clothing using double-sided tape. Marker placement included bilateral posterior-superior iliac crests, bilateral superior sacral poles, inferior sacrum, bilateral greater trochanters, bilateral midthighs, bilateral medial and lateral femoral condyles, bilateral midtibias, bilateral medial and lateral malleoli, bilateral first and fifth metatarsal heads, and bilateral calcanei (Figure 1). Two force plates (Advanced Mechanical Technology, Inc) capturing at 1200 Hz obtained joint kinetics and allowed accurate time sequencing during data collection and data processing.

Jump-Landing Task

Participants performed 3 double-limb jump-landing tasks by jumping off a 30-cm box set at 50% of their height from the force plates, followed by an immediate vertical jump. This protocol has been used previously when evaluating LE kinematics and kinetics (Figure 2).[22] Means and SDs were calculated and averaged across the 3 trials for all the collected data. The captured coordinate 3D format data were extracted from the 3D motion-analysis system and processed using Visual 3D (C-Motion, Inc).

Data and Statistical Analyses

The independent-samples *t* test for continuous variables and χ^2 analysis for categorical variables were used to assess descriptive differences between groups. Our variables of interest were sagittal-plane (internal knee-extension moment) and frontal-plane (internal knee-varus moment) moments and total sagittal-plane knee displacement for both the dominant and nondominant limbs. *Limb dominance* was defined before testing as the limb the athlete would choose to kick a ball for maximum distance. We chose these variables because they have been associated with the LE injury risk in an adolescent population.[23] Three independent-samples *t* tests (internal knee-extension moment, internal knee-varus moment, sagittal-plane knee-flexion displacement) were carried out to assess between-groups differences. We calculated Cohen *d* effect sizes to examine the differences in knee moments and knee displacement between groups for both the dominant and nondominant limbs. Effect sizes were interpreted as *small* ($>$0.2), *medium* ($>$0.5), or *large* ($\geq$0.8).[24] We used SPSS Statistics (version 25; IBM Corp) and set the α level at .05 for all statistical analyses.

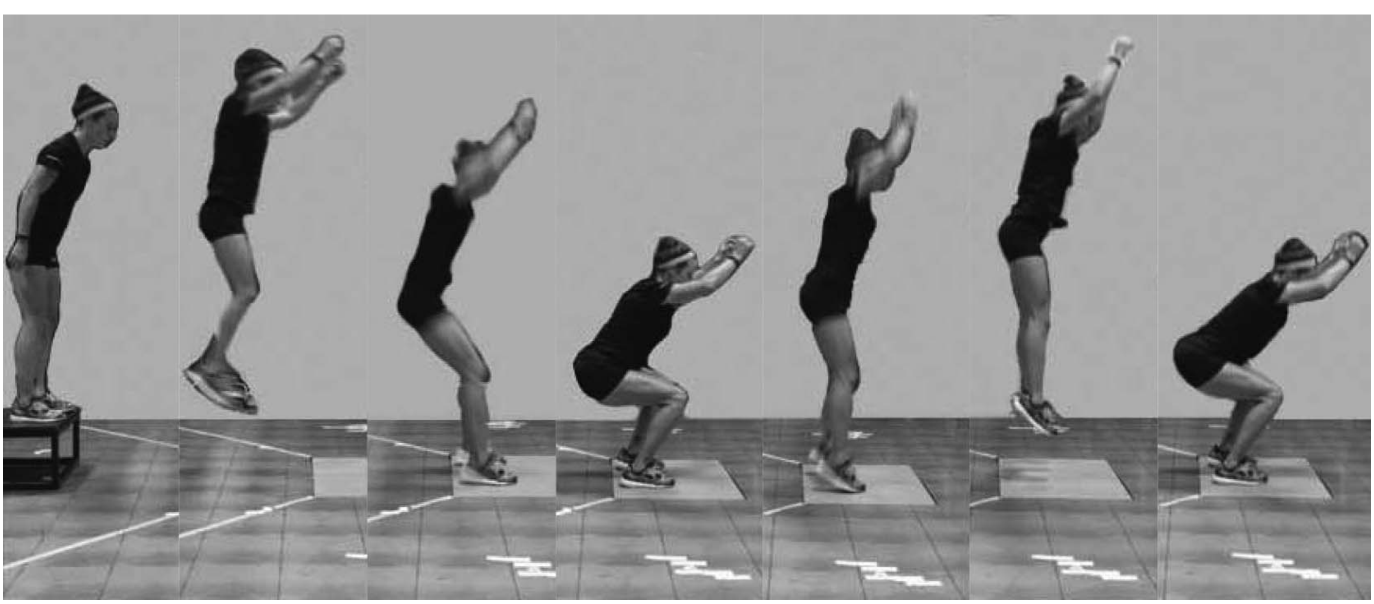

Figure 2. Jump-landing task.

Table 2. Between-Groups Comparison of Dominant- and Nondominant-Limb Knee Moments and Displacements

Knee Variable	Limb	Group, Mean ± SD		P Value
		Sport-Related Concussion	Healthy Control	
Internal-varus moment, Nm/kg	Dominant	0.024 ± 0.016	0.012 ± 0.008	.005[a]
	Nondominant	0.031 ± 0.012	0.020 ± 0.010	.005[a]
Extension moment, Nm/kg	Dominant	−0.170 ± 0.032	−0.141 ± 0.024	.003[a]
	Nondominant	−0.097 ± 0.026	−0.079 ± 0.020	.02[a]
Flexion displacement, °	Dominant	70.82 ± 10.09	83.38 ± 18.91	.01[a]
	Nondominant	73.98 ± 12.37	82.28 ± 18.80	.10

[a] Indicates difference ($P < .05$).

RESULTS

Independent *t* tests and χ^2 analysis showed no differences in any of the participants' characteristics (Table 1). The mean, SD, and *P* value for each variable are displayed in Table 2.

The SRC group demonstrated greater internal knee-extension moments in their dominant and nondominant limbs compared with the healthy control group (Figures 3 and 4). These differences in both the dominant (–0.028 ± 0.009 Nm/kg; 95% CI = –0.046, –0.010; $t_{40} = -3.154$; $P = .003$; $d = 0.98$) and nondominant (–0.018 ± 0.007 Nm/kg; 95% CI = –0.0328, –0.003; $t_{40} = -2.46$; $P = .02$; $d = 0.77$) limbs were significant.

Similarly, the SRC group exhibited greater internal knee-varus moments in their dominant and nondominant limbs compared with the healthy control group (Figures 5 and 6). These differences in both the dominant (0.012 ± 0.004 Nm/kg; 95% CI = 0.004, 0.020; $t_{40} = 3.01$; $P = .005$; $d = 1.02$) and nondominant (0.010 ± 0.003 Nm/kg; 95% CI = 0.003, 0.017; $t_{40} = 2.96$; $P = .005$; $d = 0.90$) limbs were significant.

For sagittal-plane knee displacement, the SRC group showed less knee-flexion displacement in their dominant and nondominant limbs compared with the healthy control group (Figures 7 and 8). The dominant-limb difference for sagittal-plane knee displacement between groups (–12.56 ± 4.67 Nm/kg; 95% CI = –22.02, –3.10; $t_{40} = -2.68$; $P = .01$; $d = 0.82$) was significant. However, the difference for the nondominant limb (–8.30 ± 4.91°; 95% CI = –18.23, 1.62; $t_{40} = -1.69$; $P = .10$; $d = 0.52$) was not significant.

DISCUSSION

Although most symptoms and deficits resolve within 2 weeks after SRC,[2,25] emerging research has suggested that subclinical deficits in cognitive function,[26] reaction time,[27,28] gait,[7,14,20,29] and neuromuscular control[19,30] remain long after an athlete returns to play. We found differences in dominant-limb movement patterns between participants who returned to sport within 60 days of SRC and participants who were healthy. Specifically, the dominant limb of the SRC group demonstrated greater varus moment (greater knee valgus) at the knee, increased knee-extension moment, and decreased total knee-flexion displacement in the dominant limb compared with the matched limb of the healthy control group. Based on earlier literature regarding anterior cruciate ligament injury, increased knee abduction[31] and an increased quadriceps-dominant pattern[32] during landing may lead to an increased risk of LE injury. Supporting these data, researchers[33] recently identified a higher rate of previous concussion in participants who tore their anterior cruciate ligament compared with healthy control individuals.

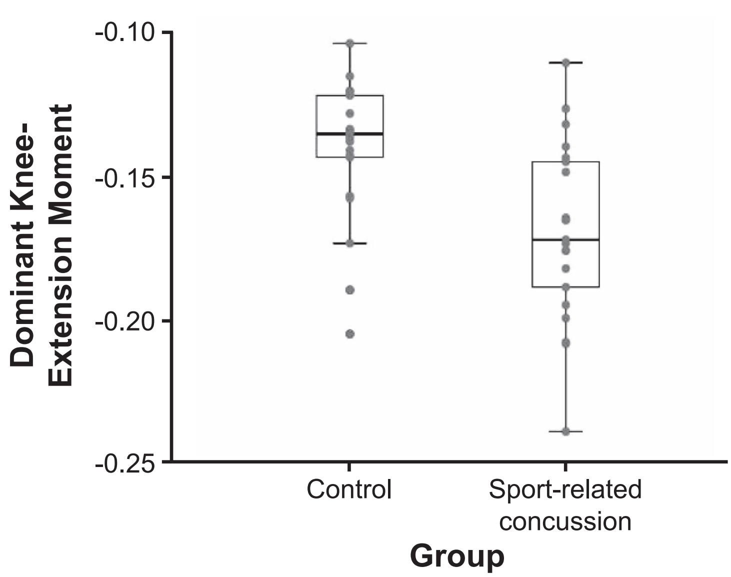

Figure 3. Dominant knee-extension moment (Nm/kg) in the healthy control and sport-related concussion groups. The boxes represent the interquartile range (IQR), with the bottom and top indicating the 25th and 75th percentiles, respectively. The horizontal line inside the boxes represents the median. The whiskers represent the range of data points from 1.5 times the IQR on either end of the IQR. The dots represent data points, with those outside the whiskers representing outliers.

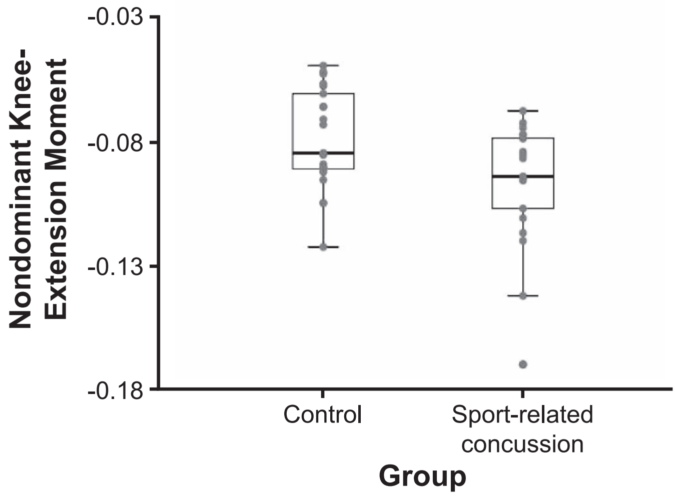

Figure 4. Nondominant knee-extension moment (Nm/kg) in the healthy control and sport-related concussion groups. The boxes represent the interquartile range (IQR), with the bottom and top indicating the 25th and 75th percentiles, respectively. The horizontal line inside the boxes represents the median. The whiskers represent the range of data points from 1.5 times the IQR on either end of the IQR. The dots represent data points, with those outside the whiskers representing outliers.

Our study is consistent with the work of Lapointe et al,[19] who found differences in knee kinematics after SRC: specifically, an increase in knee abduction and internal rotation during a jump-cut maneuver under multiple conditions after SRC. Furthermore, participants who had sustained a concussion landed in increased knee valgus under unanticipated versus anticipated conditions. However, their postinjury window ranged from 0.9 to 6.5 years after concussive injury. In an investigation of collegiate athletes, Dubose et al[30] observed that athletes who sustained a concussion during a season displayed changes in single-limb drop-landing mechanics compared with athletes in the previous season. In particular, the athletes who sustained a concussion landed with increased hip stiffness and decreased knee and overall leg stiffness compared with those athletes who did not sustain a concussion. The authors suggested that this shift toward a

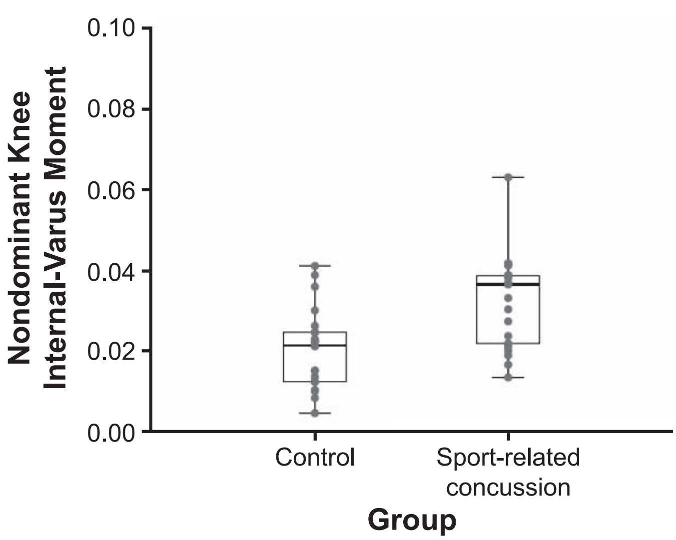

Figure 5. Nondominant knee internal-varus moment (Nm/kg) in the healthy control and sport-related concussion groups. The boxes represent the interquartile range (IQR), with the bottom and top indicating the 25th and 75th percentiles, respectively. The horizontal line inside the boxes represents the median. The whiskers represent the range of data points from 1.5 times the IQR on either end of the IQR. The dots represent data points, with those outside the whiskers representing outliers.

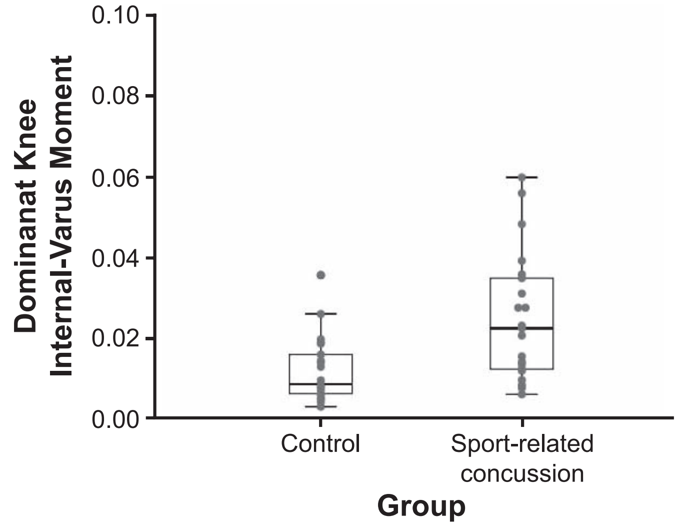

Figure 6. Dominant knee internal-varus moment (Nm/kg) in the healthy control and sport-related concussion groups. The boxes represent the interquartile range (IQR), with the bottom and top indicating the 25th and 75th percentiles, respectively. The horizontal line inside the boxes represents the median. The whiskers represent the range of data points from 1.5 times the IQR on either end of the IQR. The dots represent data points, with those outside the whiskers representing outliers.

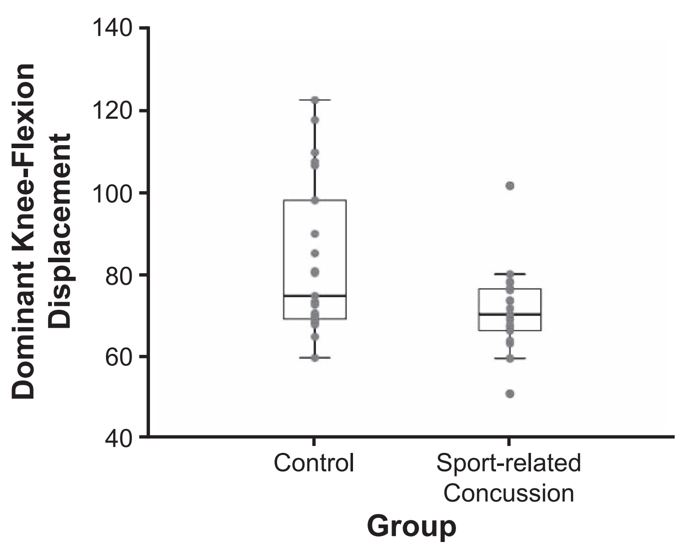

Figure 7. Dominant knee-flexion displacement (°) in the healthy control and sport-related concussion groups. The boxes represent the interquartile range (IQR), with the bottom and top indicating the 25th and 75th percentiles, respectively. The horizontal line inside the boxes represents the median. The whiskers represent the range of data points from 1.5 times the IQR on either end of the IQR. The dots represent data points, with those outside the whiskers representing outliers.

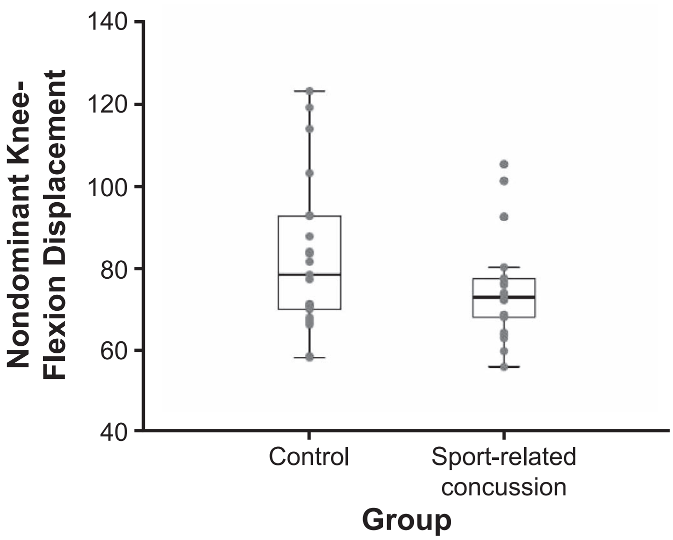

Figure 8. Nondominant knee-flexion displacement (°) in the healthy control and sport-related concussion groups. The boxes represent the interquartile range (IQR), with the bottom and top indicating the 25th and 75th percentiles, respectively. The horizontal line inside the boxes represents the median. The whiskers represent the range of data points from 1.5 times the IQR on either end of the IQR. The dots represent data points, with those outside the whiskers representing outliers.

more ligament-dominant movement pattern may be related to the increased risk of LE injury after SRC.[30]

The relationship between a history of concussion and LE injuries may have some basis in the gait changes seen after concussion. Earlier researchers showed that athletes had difficulty with dual-tasking conditions after SRC, including increased medial-lateral sway,[6,29] decreased speed,[34] a more conservative gait pattern,[7,9] increased deviations in interjoint coordination,[8,34] and deviations in turning gait.[14] Whereas these findings are important, they are confined to dual-task events performed while walking and do not include the effects of higher-level multitasking required for sport-specific movements. Perhaps athletes who present with subclinical deficits in gait patterns with walking while answering questions or performing a simple simultaneous task would have at least as much, if not more, difficulty with skills such as running and cutting while playing sports. Also, sport-related tasks are often multidimensional, and athletes may be instructed to pay attention to, read, and react to >2 tasks at a time.

To our knowledge, we are the first to evaluate biomechanical differences in a jump-landing task within a short time of returning to play in athletes who were previously concussed. Moreover, the mean age of participants with SRC in our study (15.38 $\pm$ 1.77 years) was much lower than reported in an earlier study (20 $\pm$ 2 years).[19] Using a narrower window for assessing LE mechanics after SRC allows us to reduce the potential effects of confounding variables, such as the occurrence of other LE injuries, detraining, and lack of athletic participation. In our work, athletes who were tested within 60 days of RTP demonstrated increased knee valgus, loading of the knee, and knee stiffness in the dominant limb during a jump-landing task compared with the healthy control group.

Subclinical deficits and changes in movement patterns after SRC may be related to the increased risk of LE injury substantiated in the literature. The alterations we found in dominant-limb biomechanics between athletes who had sustained an SRC and healthy control individuals may help to explain part of the relationship between a history of concussion and LE injuries.

Our research had several limitations. First, although participants were sex matched between groups, female participants predominated. Earlier investigators[35] noted clear kinematic differences between sexes with landing patterns that could have skewed the data. Second, we compared matched control participants with athletes who had sustained concussions, and, as such, no direct preinjury and postinjury effects can be determined. Third, at this time, no data are available on the connections of these LE kinematic and kinetic differences and the development of actual LE injuries in the individuals we studied. Future authors should evaluate biomechanical changes after concussion and the subsequent LE injury risk longitudinally to compare healthy athletes and those who sustained or do not sustain an LE injury after SRC.

CONCLUSIONS

Athletes who had been cleared for return to sport within 60 days after SRC landed with an increased internal knee-varus moment with increased loading through the knee and decreased knee flexion in the dominant limb compared with the healthy control group. This finding adds to the growing body of literature that has demonstrated movement-pattern differences between athletes who sustained an SRC and healthy control participants. As further evidence continues to emerge about the relationship between a history of concussion and an increased LE injury risk up to 1 year and beyond the initial injury, biomechanical analysis may offer insight into the possible mechanisms underlying this relationship. Investigators should continue to evaluate biomechanical changes and track the relationship to injuries sustained after SRC. Furthermore, researchers should compare pre-SRC movement patterns with postinjury patterns and their relationship to the development of LE injuries after SRC.

ACKNOWLEDGMENTS

We thank the clinical research coordinators at Texas Health Sports Medicine for their assistance in this study.

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Address correspondence to Bobby Jean Lee, DPT, PT, Texas Health Sports Medicine, 800 5th Avenue, Suite 150, Fort Worth, TX 76104. Address email to bobbyjeanlee@texashealth.org.