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*Review Article*

# The Influence of Sport-Related Concussion on Lower Extremity Injury Risk: A Review of Current Return-to-Play Practices and Clinical Implications

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ABSTRACT

***International Journal of Exercise Science 13(3): 873-889, 2020.*** Sport-related concussions (SRCs) are now classified as a major health concern affecting athletes across all sporting levels, with recent evidence suggesting upwards of 3.8 million SRCs occur each year. Multiple injury surveillance datasets have recently determined that athletes post-SRC, compared to non-concussed counterparts, are at greater risk for lower extremity (LE) injury beyond the resolution of traditional SRC assessment batteries. However, it is presently uncertain if common clinical practices (symptom reporting, neuropsychological (NP) examination, and static postural control analysis) can determine athletes at risk for LE injury following an SRC. A comprehensive review of the literature determined that these tools may not reveal subtle cognitive and neuromuscular deficits that lead to subsequent LE injury during dynamic sporting tasks. Current return-to-play (RTP) protocols should consider clarifying the addition of specific objective locomotor analysis, such as gait tasks and sport-specific maneuvers, to determine the risk of LE injury after an athlete has sustained an SRC.

KEY WORDS: Brain injury, biomechanics, anterior cruciate ligament, musculoskeletal injury

## INTRODUCTION

A concussion can be classified as a brain injury of various severity induced by (1) impact directly to the head and/or (2) impulsive forces acted on other body areas that are transmitted to the head, leading to a complex pathophysiological cascade of damaging events (56). An "energy crisis" occurs as the brain attempts to restore ionic balance following injury, a mechanism believed to lead to acute psychological, behavioral, and locomotor alterations commonly seen in those post-concussed (27). An athlete may experience a multitude of symptoms, including headache, blurred vision, slowed reaction time, photophobia, and abnormal locomotor patterns (28, 45, 64). With approximately 1.6–3.8 million sports-related concussions (SRCs) occurring each year in the United States (46), it is imperative to determine when an athlete is safe to resume sport. To ensure an athlete's safety following an SRC, clinicians typically administer a variety of assessment batteries. These tools include symptom reporting and monitoring the time-to-symptom resolution (16, 25), neuropsychological (NP) analysis (18), and static balance/postural control testing (15, 65). While undergoing these clinical examinations, athletes are re-introduced into sport utilizing a graduated activity procedure, progressing through each activity step without symptom provocation (56). Under the current SRC assessment paradigm, an athlete is typically cleared to resume sport within 14 days post-injury based on self-report of symptom resolution and returning to baseline on various clinical examinations (e.g., NP and balance testing; 16, 56). However, significant issues arise when utilizing these traditional measures to evaluate an athlete's physical and cognitive readiness following an SRC. Athletes may underreport or hide symptoms from medical personal for fear of missing playing time (57) or due to cultural perceptions that an SRC is a sign of weakness (76). Athletes can purposefully perform poorly on baseline NP screenings in order to subsequently exceed these scores following an SRC, thereby allowing for a faster RTP (77). Traditional balance measures, such as the Balance Error Scoring System (BESS), are limited to the subjective judgement of the test administrator (1), while objective balance tools (e.g. Sensory Organization Test, SOT) are limited to static postural analysis that does not replicate sport-specific demands (24). Additionally, the SOT requires expensive and immobile equipment, drastically reducing the utility in most sports medicine settings. While static balance assessments provide measures of postural control, more clarity regarding their clinical utility is necessary to incorporate these modalities into the consensus-based RTP guidelines (56).

While the aforementioned tools provide significant insight into SRC injuries, they are limited in their applicability to locomotor-related tasks. Given that athletes are exposed to both cognitively and physically challenging tasks during sport, researchers and clinicians utilize dual-task movement analyses within a RTP protocol. Gait analyses in athletes previously concussed have revealed locomotor instabilities (8, 9) that may translate to further instability within more demanding sport environments. During dual-task gait examinations, athletes post-SRC demonstrated significant deficits in gait velocity and frontal/sagittal plane stability (49). When paired with a cognitive task, deficits in locomotor abilities may persist weeks beyond symptom resolution and a return to NP baseline scores (19), suggesting variable recovery rates exist amongst SRC assessment modalities (50). Residual SRC impairments after clearance for RTP, including a failure to report symptoms or subtle functional deficits, may place an athlete at greater risk for LE injury (36).

Recent evidence suggests that adolescent (53) and collegiate athletes (26, 34, 52) are at a significantly greater risk for lower body injury following an SRC. This risk has been noted to be present upwards of one year after the concussive event, as collegiate athletes with an SRC history displayed greater injury rates (64–67% increase) compared to control groups during this time period (22, 52). It should be noted that athletes that were previously concussed were medically diagnosed by sports medicine personnel and underwent clinical examinations that adhered to the latest SRC consensus at the time of study (22, 34, 52, 53). In light of these findings, researchers have initiated biomechanical studies of sporting movements post-SRC to provide an objective rationale for this newfound relationship. Individuals with a prior concussive history displayed greater knee valgus and knee internal rotation during a jump-cut maneuver (47), along with changes in LE stiffness during a jump-landing task (17). These studies suggest altered neuromuscular control (17), potentially placing an individual at greater risk for LE injury during an athletic maneuver. However, limitations such as single-trial analysis (17) or lack of a complete

LE dataset (47) limit our current understanding of the influence of SRC injury on LE biomechanics during sporting maneuvers. Further study of sport-specific tasks is needed to provide a rationale for why post-SRC athletes are sustaining LE injuries at a greater rate than athletes without an SRC history (52). Thus, the purposes of this narrative literature review are threefold: (1) to examine the current literature describing the relationship between SRC and future LE injury risk; (2) to describe current clinical assessment techniques post-SRC and their association to LE injury risk following clearance to resume sport; (3) to propose future areas of research to further delineate the relationship between SRC and LE injury. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (58).

## LITERATURE and FINDINGS

*Risk of LE Injury Following an SRC:*

Over the previous 5 years, a newfound relationship between LE injury and SRC has been established in various sporting populations. Athletes at the high school (53), collegiate (22, 26, 34, 52), and professional (59, 66) levels have demonstrated a greater risk for sustaining a LE injury post-SRC. The majority of the aforementioned studies consist of retrospective injury surveillance data that monitored LE injury rates in both athletes concussed and non-concussed for a specified time period around the initial SRC event (both prior to- and post-SRC). All athletes diagnosed with SRC in these investigations were clinically cleared to resume sport by sports medicine personnel (athletic trainer, physician) and monitored for LE injury rates at various time points after the initial SRC. Of note, it is unclear if the individuals responsible for clearing athletes strictly adhered to all components related to the latest SRC consensus (56).

High school athletes tend to require greater recovery time from an SRC compared to higher level counterparts (15). Following the resolution of concussive symptoms and clinical clearance to resume sport, it appears that high school athletes are at greater risk for sustaining a LE injury compared to pre-concussive LE injury rates. In a recent study of 18,216 male and female high school athletes, investigators determined that the risk of LE injury resulting in time-loss from sport (defined as greater than the day of injury) increased by 34% for every previous SRC (53). However, a prior SRC did not result in greater risk of a non-time loss injury, although a clear distinction between non-time loss versus time-loss LE injury following an SRC is presently unclear (53). While the aforementioned investigation provides insightful information regarding LE injury risk post-SRC in a large high school athletic population, further research is necessary to confirm these findings.

Numerous studies also suggest that collegiate athletes are at greater risk for LE injury at 90 days (4), 180 days (52), and 365 days (22, 52) post-SRC. Collegiate male and female athletes across seven sports were 2.5 times more likely to sustain a LE musculoskeletal injury compared to matched counterparts 90 days after sustaining an SRC (4). It was determined that 17% of post-SRC athletes sustained a non-contact LE injury, while the incidence of similar injury was less (9%) in the matched control group (4). In a related study of collegiate basketball, soccer, and lacrosse athletes, LE musculoskeletal injury risk was 3.4 times greater in athletes who were previously concussed when matched to those of comparable athletic status during a 90 day follow-up period (26). Male football athletes with prior SRC were 3.7 times more likely to injure the LE, while female sport participants demonstrated a 2.8 times greater risk for LE injury after SRC (26). These findings at 90 days post-SRC have not been observed in other collegiate cohorts (52), although it is presently unclear why these findings are equivocal. While Lynall et al. (2015) did not observe differences at 90 days, athletes were significantly more likely to sustain a LE injury at 180 days (2.02 times) and 365 days (1.97 times) post-SRC compared to pre-concussive injury rates (52). Elevated LE injury risk in male football athletes post-SRC has been demonstrated to extend beyond 365 days from the initial concussive event, however, caution must be given due to a small study cohort (44). These findings run counter to the belief that after an SRC, deconditioning and an athlete being "out of game shape" are significant factors for LE injury. While LE injury risk has been associated with SRC occurrence across multiple collegiate populations, previous investigations failed to control for LE injury history prior to an SRC, a potential confounding variable that may influence subsequent injury risk. For example, athletes returning from ACL reconstruction are 15 times more likely to re-injure the ACL on the contralateral or ipsilateral limb (63). When accounting for previous LE injury, Fino et al. (2017) found college athletes post-SRC to be at a 67% greater risk for subsequent LE injury when matched to those of the same team (22). While the exact location of LE injury following SRC was unclear in the aforementioned studies, Gilbert et al. (2016) determined significant associations between SRC (reported, unreported, and unrecognized) and lateral ankle sprain, knee injury, and LE muscle strain (26). This investigation consisted of 335 athletes (61% female) who completed a questionnaire pertaining to their injury history following the completion of their collegiate career. Although limitations exist due to self-report and an inability to determine order of injury occurrence, athletes with a stated SRC history were 1.6-2.9 times more likely to report a LE injury (26), findings similar to related retrospective data (52).

In addition to youth and collegiate athletes, professional athletes have demonstrated greater injury risk and frequencies following SRC. Elite male European football athletes were at greater risk for subsequent injury (combined lower and upper extremity) following SRC occurrence across three time periods (0–3 months, 3–6 months, and 6–12 months post-SRC), with injury risk being greatest at 6–12 months after an SRC (59). Following 28 seasons of injury data in professional ice hockey players, researchers concluded that, in comparison to a knee injury, athletes post-SRC were more likely to sustain a subsequent severe injury (> 28 days recovery) within 21 days of returning to sport (60). However, no differences were reported at the seven and 42 day follow-up and the reported injury after the SRC or knee injury was not classified by location (59). Furthermore, no differences were observed in the frequency of subsequent injury between athletes who sustained an SRC or knee injury (60). When examining the association between subjectively reported SRC and LE injury frequency during a professional career, National Football League athletes who reported one, two, or three or more concussions had up to 63%, 126%, and 165% greater odds of sustaining a LE musculoskeletal injury (66). In this sample of 2,429 retired athletes, a greater number of reported SRCs were associated with more injuries to the ankle-foot (Achilles rupture, ankle ligament rupture, and ankle-foot fracture) and knee (ACL and meniscus tear; 66), suggesting a dose-response relationship between SRC and LE injury. Although not explicitly highlighted by the authors in the aforementioned studies on professional hockey and American football athletes (60, 66), the evolving definition of SRC and criteria for clearing athletes to RTP may have influenced injury reporting in these athletic cohorts.

Mounting evidence suggests that athletes with a prior SRC history across all sporting populations are at greater risk for LE injury, although the mechanism for this relationship is presently unclear. Multiple theories have been postulated, such as impaired motor planning and coordination (17), reductions in cortical excitability (26), and neuromuscular alterations (4) that persist far beyond resolution of traditional post-SRC measures (37). It has been demonstrated through numerous studies that following a concussive event, the majority of athletes are able to return to baseline values relating to symptom reporting, NP performance, and balance/sway within a relatively short time period. However, subtle cognitive and physical deficiencies may still persist, only to be revealed during a dynamic sporting environment that tasks performers with completing highly complex maneuvers (38). The sporting demands placed upon an athlete are influenced by a number of factors, including an individual's neuromuscular characteristics, the intended movement goal, and the external environmental stimuli, all of which may not be typically accounted for within the currently implemented, gradual RTP protocol after an SRC occurrence. Furthermore, the utilization/interpretation of RTP guidelines may also influence LE injury risk following an SRC. For example, some practicing clinicians may utilize dual-task gait analysis whereas others may incorporate a single-task procedure, ultimately leading to clearing an athlete at different time points based on same management stage. Differing practices among individuals responsible for SRC management may influence RTP timelines and LE injury risk in athletes with recent SRC. However, the exact RTP modalities utilized by clinicians have yet to be elucidated in the current literature. Future research should determine if differences exist among disciplines (e.g., ATC, MD, PT) in the type of rehabilitation protocols utilized to clear an athlete following SRC. These findings would provide substantial value to determine how varying clinical practices for SRC management associate to LE injury risk.

*The Relationship between Cognitive Function and LE Injury:*

Recent evidence suggests that cognitive deficits, a hallmark of SRC, play an integral role in LE injury risk during sport. Examinations between musculoskeletal injury and cognition determined that collegiate athletes currently injured in the upper or lower extremity performed worse on matching tasks than healthy controls, and no statistical differences were found between athletes with a musculoskeletal injury or SRC on any neurocognitive metrics (40). Young adults classified as "low performers" on a NP test battery displayed biomechanical patterns suggesting a greater risk for ACL injury when performing dual-task drop landings (34). Compared to "high performing" individuals, those with a lower score completed landings with greater vertical ground reaction forces, anterior shear forces, knee abduction moment/angle, along with decreased trunk flexion angle (34). An athlete with deficiencies in processing environmental stimuli and task constraints (such as an athlete post-SRC), along with the inability to preplan correct movement sequences, may not be able to produce protective muscular forces, thus leading to high impact loads on musculoskeletal components that result in injury (74). Subtle, yet lingering cognitive deficits upon return-to-sport following an SRC may influence an athlete's ability to perceive external stimuli (spatial relationships among the teammates, opposition, and the playing apparatus), eliminate extraneous variables (e.g. crowd noise), and execute proper movement sequencing within a dynamic sporting environment. Under increased cognitive loads, slight impairments in motor planning and information processing may lead to joint instability, thus resulting in injury to the LE (42). It is recognized that the relationship between cognition and LE injury is still in its infancy and that more research is necessary to further delineate the influence of cognitive performance on LE injury risk in both concussed and non-concussed sporting populations.

*Traditional SRC Assessment Tools*:
Following an SRC, an athlete is asked to complete multiple screening measures, including symptom reporting, NP testing, static balance/postural control tasks, and a RTP protocol that gradually incorporates dynamic activity. The following sections will provide an overview of these assessment modalities, as well as their association (if any) to LE injury risk.

*Symptom Reporting:* A variety of methods have been employed to determine the severity, and subsequent recovery period, of an SRC. The hallmark of a concussive injury is symptom presentation that tends to be most severe 24–48 hours post-SRC (51). While headache is the most common injury symptom among amateur (25), collegiate (28), and professional (64) competitors, athletes may experience a wide range of symptoms that affect cognition, consciousness, anxiety, sleep, locomotor capabilities, and sensitivity to external stimuli (i.e. light and sound; 45). Symptom resolution following an SRC, as reported by athletes, may range from three days (25) to multiple weeks (15). Prior study determined that the majority of athletes are asymptomatic by day seven (21), however, more recent evidence in adolescent athletes suggests that symptom resolution may last up to 14–16 days (15). Significant issues arise when establishing RTP protocols solely off symptom endorsement, attributed to underreporting behaviors (57) and lack of awareness relating to common SRC symptoms (77). Additionally, athletes may report mild symptoms during baseline screening, including headache and fatigue (16), which complicate symptom assessment. A recent investigation pertaining to reporting behaviors in collegiate athletes (the majority being football athletes) determined that athletes underreport post-SRC symptoms to team medical personal when compared to a private third-party setting (i.e. brain injury institute; 57). Furthermore, 60% of athletes who were cleared to RTP indicated at least one mild symptom and no differences existed in symptoms reported between cleared and non-cleared athletes nine days post-SRC (57).

*The Link to LE Injury:* Presently, there is not a clear association between symptom presentation and subsequent LE injury. Self-reported dizziness during an on-field assessment, a potential sign of more serious vestibular dysfunction, was found to be associated with a 6.3 times greater risk of SRC recovery lasting longer than 21 days (48). A loss or decrease of vestibular function can significantly impact one's postural control, with numerous researchers suggesting this system is significantly affected in athletes post-SRC (30, 31, 65). However, it is unclear if athletes who report dizziness are at greater risk for LE injury compared to other reported symptoms. While an athlete is not allowed to resume sport until all symptoms have resolved, initial symptomology may be indicative of future subtle impairments that affect various body systems responsible for proper perception-action integration (e.g. visual, proprioceptive and somatosensory systems). Future research is warranted to determine if specific SRC symptoms are associated with LE injury in concussed athletes.

*NP Examination:* In addition to symptom evaluation, NP testing has become a popular screening instrument for athletes at risk for SRC. Evaluation of NP performance allows for objective analysis following a concussive event, increasing sensitivity to cognitive impairments beyond symptom resolution (3). Various NP assessment batteries have demonstrated that athletes post-SRC display deficits during tests of information processing (65), short/long delay recall (32), oculomotor speed (70), and visuospatial memory (40) within the acute recovery phase. While recommended during the recovery from an SRC, recent evidence has shed insight on some limitations associated with NP evaluation. Suboptimal performance during baseline screening (77) and practice effects from frequent exposure to NP testing within an acute time period (7) may limit the effectiveness of these assessments for determining when an athlete is healthy to resume sport.

*The Link to LE Injury:* There is evidence to suggest that NP performance is associated with LE injury risk in various sporting populations (73, 79). Interestingly, in a study of collegiate athletes who were administered the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) test battery at baseline, those who sustained a non-contact ACL injury demonstrated slower reaction times and processing speed, as well as deficits in visual and working memory, when compared to matched, injury-free controls (73). Collegiate football athletes who completed the ImPACT composite reaction time assessment with a performance ≥ 0.545 seconds were more than twice as likely to sustain a LE sprain or strain over the course of a competitive season (79). The aforementioned studies were among the first to suggest that ligamentous or musculoskeletal injury is associated with impaired NP test performance that is commonly seen acutely after a concussive event (i.e., one week post-injury). While the studies by Swanik et al. (2007) and Wilkerson (2012) suggest an association between NP performance and LE injury risk, all athletes within these collegiate cohorts were free from SRC. Future research should address whether athletes post-SRC demonstrate similar NP performance and the influence of this performance on LE injury risk.

*Static Balance and Postural Control:* Along with symptom reporting and NP test batteries, it is important to identify balance and postural control deficiencies often present after a concussive injury (30). The maintenance of balance and one's sense of spatial orientation are thought to be directly influenced by the vestibular system, a sensory organ in the inner ear (75). A loss or decrease of vestibular function can significantly impact one's postural control, with numerous researchers suggesting this system is significantly affected in concussed athletes (30, 31, 65). This may be due to potential peripheral receptor damage or lack of cerebral integration of the vestibular system with the visual and somatosensory systems (31). Given that vestibular deficits may influence SRC recovery outcomes, clinicians and researchers have developed static balance and postural control tools to provide quantifiable measures of recovery. The two most common measures are the BESS and SOT. The BESS is composed of three stance conditions (double-leg, single-leg, and tandem) performed with the eyes closed on a firm and foam surface (31), while the SOT includes six conditions that determines sensory deficits in one's visual, vestibular, and proprioceptive systems (31).

There is a large body of evidence suggesting that athletes demonstrate static balance deficits during the acute SRC recovery phase. Static balance impairments measured by the most commonly researched tools, BESS and SOT, typically resolve within three to five days after the concussive event (15, 31). Caution is suggested when administering the BESS and SOT, as the resolution of postural instability may not be suggestive of complete recovery (15, 77). Furthermore, recent comprehensive reviews of the SRC literature question the practicality of both the SOT and BESS (31) due to its analysis of static posture not representative of the dynamic movement patterns athletes perform during sport.

*The Link to LE Injury:* Currently, there is no evidence to suggest that static balance/postural control deficits measured by the BESS and SOT are associated with greater risk for LE injury in athletes with SRC. However, multiple research groups have reported that worse performance on dynamic balance measures are related to an increased risk for LE injury in collegiate football (6) and high school basketball (67) athletes. All athletes in these investigations were free from SRC and followed prospectively over the course of a single competitive season. Future research is warranted to determine if specific modalities within the BESS or SOT demonstrate predictability for LE injury risk post-SRC.

*Locomotor Alterations Post-SRC:*
As part of the latest consensus-based recommendations for RTP following a concussive injury, it is imperative that athletes perform light aerobic activity (e.g., walking, riding a stationary bike) without symptom provocation (56). Additionally, researchers have utilized motion-capture and force platform technologies during gait analyses post-SRC to determine whether subtle locomotor deficits persists beyond symptom resolution. Dynamic postural control during sport is crucial for minimizing injury risk; therefore, athletes that demonstrate altered gait after SRC may not be fit to RTP, even in light of symptom resolution and return to baseline on NP and balance examinations (5). For example, Buckley et al. (2013) determined that individuals who are concussed alter their peak propulsive and breaking forces at least 10 days after the concussive event (5). Locomotion analysis post-SRC may provide the clinician with greater detail relating to injury severity and recovery outcomes as it relates to a dynamic task. Typical variables of interest during a gait examination post-SRC may include: spatio-temporal parameters (e.g. gait speed, cadence, step width, stride length/time), sway in the sagittal and frontal planes, along with center of mass and center of pressure measures. Following a concussive event, it is speculated that the recovery of motor performance is unaligned with cognitive function (5, 12), therefore, continued presentation of altered gait strategies, past resolution of traditional clinical outcomes, may provide greater sensitivity as to when an athlete should resume sport.

*Single or Dual-Task Gait:* While gait analysis post-SRC is commonly assessed under a single-task (i.e. level walking) condition (5, 20, 61), it appears that single-task gait fails to elicit abnormalities in gait velocity (37, 80), sagittal and frontal plane sway (37, 61), and joint coordination (10, 11) outside of the acute phase of recovery. Therefore, inclusion of additional cognitive or motor tasks (i.e. dual-task) during ambulation may reveal subtle deficits post-SRC during clinical evaluation (20). Athletes are required to complete both motor and cognitive tasks simultaneously during sport, therefore, dual-task gait analysis may be more appropriate for detecting impaired dynamic postural control in both the acute and chronic phases of recovery from SRC (23). After reporting symptom resolution, adolescent athletes post-SRC did not demonstrate differences in spatio-temporal parameters (speed, cadence, stride length, double support time) during single-task walking when compared to controls, however, gait deficits were revealed under dual-task conditions (2). Specifically, athletes who were asymptomatic performed dual-task gait with slower walking velocity, shorter cadences and decreased stride length (2). Cognitive tasks secondary to level walking typically consist of a series of continuous questions-and-answers, tasking individuals with reciting words and months in reverse order and/or counting backwards from a designated number (9, 11, 61). Additional tasks may include a visual or auditory Stroop test (20, 60), a measure of parallel processing (54), during gait. When performing dual-task walking with a cognitive component, males and females analyzed within 48 hours of a concussive event demonstrated slower gait velocity and increased frontal plane sway compared to matched controls (60). Even while adopting a slower, more conservative gait pattern, individuals previously concussed were unable to maintain dynamic stability in the frontal plane (61). Decreased gait velocity was noted at two days post-injury in a larger participant group, although this gait parameter returned to control levels by day six and continued to increase 4 weeks after the concussive event (9). Additionally, no differences were detected between participants who were previously concussed and matched controls in frontal plane sway at any time point (9), although other researchers have determined greater frontal plane sway in adolescent (37) and collegiate athletes (62) post-SRC. When matched with healthy adolescents, athletes had significantly greater dual-task costs (defined as percentage change from single- to dual-task conditions) for gait velocity and frontal plane sway across five separate time points following an SRC (72 hours, 1 week, 2 weeks, 1 month, and 2 months (37). Adolescents with an SRC history were also significantly more prone to error during an auditory Stroop task while ambulating (37), with these findings being supported during visual Stroop tests in young adult athletes (19, 20).

*Complex Gait:* Although dual-task gait analysis has demonstrated abnormal locomotor patterns both acutely and chronically post-SRC, complex gait tasks may provide further insight pertaining to locomotor capabilities in concussed athletes. Complex gait, suggested as "walking on uneven surfaces or in crowded environments requiring obstacle avoidance and navigation" (23), may also include cognitive components similar to dual-task conditions (14, 19). These gait conditions require greater motor and cognitive demands, placing particular emphasis on obstacle avoidance, executive functioning, spatial awareness, and rapid information processing (19, 20, 22), all necessary components for injury avoidance. An elite male junior hockey athlete demonstrated significantly slower approach gait velocity and circumvented around a cylindrical obstacle with less clearance during complex gait conditions at seven and 30 days after an SRC, suggesting impaired obstacle avoidance beyond symptom resolution (19). However, under similar complex conditions, young adult male and female athletes who were asymptomatic at the time of testing performed the navigational task with greater clearance than control athletes (20). Although differences between the aforementioned studies were noted in obstacle clearance, both investigations showed greater dual-task costs (measured as response reaction time) when a cognitive component was implemented during gait trials (19, 20). Some restraint must be given to these studies due to low sample size (19, 20), however, other researchers have determined that individuals display slower tandem gait completion time and movement cadence up to two months after a concussive event (39). During an obstacle avoidance task, young adults walked significantly slower an average of 158 days post-SRC when compared to controls (14). Following a concussive event, it is speculated that motor performance recovery is not associated with cognitive function as measured with standardized NP assessments (5, 12), therefore, continued presentation of altered gait strategies past resolution of traditional clinical outcomes may provide greater sensitivity pertaining to when an athlete should be cleared for sport participation. Overall, there appears to be clinical utility in assessing gait performance under complex conditions (23), but a paucity of available evidence limits any definitive conclusions as to how these practices should be implemented during recovery from an SRC.

*The Link to LE Injury:* Gait analysis has been used to predict LE overuse injury (71) and to examine altered biomechanical patterns following LE injury (43). Adolescent athletes post-SRC who sustained a subsequent musculoskeletal injury during a one-year follow-up period demonstrated increased dual-task cost walking speed from the initial concussive event to clinical recovery (36). However, there remains a paucity of evidence relating the risk of LE injury to gait alterations in athletes with SRC, warranting the need for further study. Overall, it appears that athletes post-SRC adopt a conservative locomotor strategy during the acute recovery phase, however, chronic abnormalities are also present under more difficult task demands. Following an SRC, athletes performing dual-task and/or complex gait demonstrate impaired dynamic stability and obstacle avoidance, suggestive of deficits in executive functioning, spatial awareness, and rapid information processing (19, 20) that may attribute to subsequent risk of LE injury. Objective analysis of altered gait strategies during a complex task post-SRC may be a sign of locomotor deficiencies that lead to LE injury, although this statement has not been substantiated by the current literature.

*SRC and Sport-Specific Biomechanics:* LE injury mechanisms following SRC have not been described by the aforementioned retrospective surveillance studies (44, 52, 53). To provide a potential objective rationale for the relationship between SRC and LE injury, researchers have initiated examinations of biomechanical movement patterns during dynamic, sport-specific tasks. Compared to pre-season measures, collegiate football athletes post-SRC demonstrated alterations in hip, leg, and knee stiffness during a unilateral landing task, while no differences were detected in healthy controls (17). Decreased leg stiffness, previously associated with Achilles tendinopathy (6) and hamstring injury (68), was found during the post-season landing trials (17). In a study of young adults performing multidirectional jump-cutting maneuvers with concurrent Flanker tasks, investigators reported that individuals previously concussed were at greater risk for knee injury relative to matched controls (47). Those with prior concussion demonstrated greater knee valgus and internal rotation on the cutting limb, movement patterns often associated with a non-contact ACL injury (69). These studies were the first to reveal that individuals with a prior concussive history demonstrate LE biomechanical movement patterns that elevate the risk of LE injury (17, 47). However, these investigations carry significant limitations, highlighting the need for further exploration into LE biomechanics post-SRC. LE stiffness measures were based upon one testing trial per limb (17), even though it is recommended that a minimum of four landing trials be necessary for landing performance stability (41). Additionally, prior study on concussed individuals failed to analyze hip motion patterns nor any lower extremity kinetic variables during the jump-cutting tasks (47), both of which are suggested to play an influential role in ACL injury (68). Further LE biomechanical research may provide a more definitive rationale for the elevated risk of LE injury after an athlete has sustained an SRC.

## CONCLUSION

SRCs are a growing concern for athletes across all participation levels, particularly those involved in collision-based sports. Traditional post-SRC assessments include symptom reporting, NP evaluation, static balance/sway measures, and a dynamic stepwise progression model for determining return-to-sport, with the majority of athletes being cleared within two weeks of injury. However, these measures come with limitations such as self-report, subjective analysis, learning effects, and a lack of generalizability to a dynamic sporting environment. With recent evidence suggesting athletes to be at greater risk for LE injury after an SRC, there is a need for more objectivity and clarification in determining when an athlete should be allowed to resume sport participation. Gait alterations have been demonstrated well beyond clinical resolution of traditional SRC assessment batteries, therefore, it stands to reason that analysis of sport-specific tasks may further highlight athletes at risk for future LE injury following an SRC. The purpose of this literature review was to examine the current state of SRC research, specifically serving as an outline for the subsequent analysis of LE biomechanical patterns during dynamic sport maneuvers in various athletic populations with and without an SRC history. Recent LE biomechanical studies have provided a potential rationale for this newfound relationship between LE injury and SRC, however, it is recognized that this research is still in its infancy. Based on the available evidence related to gait and jump-landing alterations post-SRC, it is recommended that clinicians utilize objective movement analysis within a graduated RTP protocol (56). While gait and sport-specific activity are included within the latest RTP guidelines (56), it is unclear to what extent these practices are being followed when managing a recently concussed athlete. Clarification regarding consistent RTP practices among clinicians would potentially offer greater insight the relationship between management practices and their utility for mitigating LE injury risk. Future SRC management consensus should include specific recommendations regarding gait and sport-specific movement analysis to be adhered by all practicing clinicians responsible for returning an athlete to sport. Recent biomechanical evidence suggests that athletes may be at greater risk for LE injury beyond symptom resolution and clearance from the RTP model (17, 37), therefore, it is suggested that clinicians continue to monitor LE injury risk in athletes who have resumed full sport participation. Ideally, LE movement screening would be monitored up to one year post-SRC, as previous concussed athletes have demonstrated greater LE injury risk up to this time point (22, 52). Millions of SRCs occur each year during athletic participation, therefore, continued study pertaining to LE movement biomechanics post-SRC may offer the sporting community with useful movement screening protocols to reduce LE injury risk following a concussive event.

Athletes participating in football, soccer, basketball, lacrosse, and ice hockey are at a sustainably higher risk for LE injury following a concussive event (4, 22, 26, 52, 53, 59, 66). Therefore, it is proposed that future research continue to examine LE movement patterns in various athletic populations who have sustained an SRC to ascertain any neuromuscular and/or biomechanical alterations during sporting movements that provide rationale for increased LE injury risk. Given the complex nature of sport, movement analysis should include both motor and cognitive challenges for the best representation of the demands placed upon an athlete during sport. Future research would benefit from utilizing biomechanical instruments such as motion capture and force platforms to analyze LE kinematics and kinetics during sport-specific maneuvers at baseline and post-SRC time periods. The use of electromyography during these tasks may also provide insightful information as to whether concussed athletes demonstrate altered neuromuscular patterns that heighten LE injury risk (e.g., impaired hamstring musculature activity in relation to knee injury risk during sport-specific tasks). Tasks such as jump-landings and jump-cutting should be analyzed both unilaterally and bilaterally and should include external stimuli (e.g. visual, auditory, tactile) that an athlete must respond to within the given sporting maneuver. Ideally, the aforementioned movement analyses would be conducted in conjunction with consensus RTP protocols (56) as well as continued monitoring once an athlete has fully returned to sport. From this proposed analysis, researchers, sports medicine personnel, and coaches may be able to establish more objective return-to-sport protocols that encompass LE movement screening procedures to mitigate the risk of LE injury after an SRC. Based upon current RTP recommendations (56), it would be pertinent to investigate whether strict adherence to these guidelines are being practiced (by medical and non-medically trained individuals) and how adherence may impact LE injury rates in various sporting populations. For example, a physician may provide clinical clearance based upon static measures (i.e., symptom reporting, NP testing, postural analysis) while a physical therapist may incorporate gait analysis into a RTP protocol. Additionally, it is recommended that future research determine whether athletes with prior SRC sustain more severe LE injuries and/or require greater recovery time from a similar LE injury compared to matched counterparts. Findings from future investigations will further delineate the relationship between SRC and LE injury in athletic populations.

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