Perceptual-Motor Efficiency and Concussion History Are Prospectively Associated With Injury Occurrences Among High School and Collegiate American Football Players

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Background: After a sport-related concussion (SRC), the risk for lower extremity injury is approximately 2 times greater, and the risk for another SRC may be as much as 3 to 5 times greater.

Purpose: To assess the predictive validity of screening methods for identification of individual athletes who possess an elevated risk of SRC.

Study Design: Case-control study; Level of evidence, 3.

Methods: Metrics derived from a smartphone flanker test software application and self-ratings of both musculoskeletal function and overall wellness were acquired from American high school and college football players before study participation. Occurrences of core or lower extremity injury (CLEI) and SRC were documented for all practice sessions and games for 1 season. Receiver operating characteristic and logistic regression analyses were used to identify variables that provided the greatest predictive accuracy for CLEI or SRC occurrence.

Results: Overall, there were 87 high school and 74 American college football players included in this study. At least 1 CLEI was sustained by 45% (39/87) of high school players and 55% (41/74) of college players. Predictors of CLEI included the flanker test conflict effect ≥69 milliseconds (odds ratio [OR], 2.12; 90% CI, 1.24-3.62) and a self-reported lifetime history of SRC (OR, 1.70; 90% CI, 0.90-3.23). Of players with neither risk factor, only 38% (29/77) sustained CLEI compared with 61% (51/84) of players with 1 or both of the risk factors (OR, 2.56; 90% CI, 1.50-4.36). SRC was sustained by 7 high school players and 3 college players. Predictors of SRC included the Overall Wellness Index score ≤78 (OR, 9.83; 90% CI, 3.17-30.50), number of postconcussion symptoms ≥4 (OR, 8.35; 90% CI, 2.71-25.72), the Sport Fitness Index score ≤78 (OR, 5.16; 90% CI, 1.70-15.65), history of SRC (OR, 4.03; 90% CI, 1.35-12.03), and the flanker test inverse efficiency ratio ≥1.7 (OR, 3.19; 90% CI, 1.08-9.47).

Conclusion: Survey responses and smartphone flanker test metrics predicted greater injury incidence among individual football players classified as high-risk compared with that for players with a low-risk profile.

Keywords: mild traumatic brain injury; postconcussion syndrome; musculoskeletal injury; injury risk screening

Recent studies[19,23,37] have produced convincing evidence that musculoskeletal injury incidence increases after a sport-related concussion (SRC) has been sustained. The risk for musculoskeletal injury after an SRC appears to be about 2 times greater,[37] and the risk for another SRC may be as much as 3 to 5 times greater.[4,44] An additional concern is the evidence from advanced diagnostic testing procedures that SRC often produces microstructural disruption within white matter tracts, which may increase susceptibility to psychiatric and neurodegenerative conditions.[35,42,47] Current clinical guidelines for return to sport activity after SRC reflect an assumption that resolution of acute symptoms corresponds to restoration of normal brain function[24]; however, a growing body of evidence suggests that asymptomatic neuroinflammatory processes can persist for months or years.[11,12,17]A key concern is the potential for adverse subacute or long-term outcomes if subtle impairment remains undetected and further brain injury is sustained from sport participation.[5] Repetitive SRC has the potential to exacerbate a chronic

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neuroinflammatory response within the brain[33,50] and further elevate the risk for lower extremity injury.[23] American football presents an exceptionally high risk for occurrence of SRC and musculoskeletal injury, with sprain or strain of anatomic structures in the body core or in the lower extremity being the most common injuries.[31]

A recent review of the literature found no convincing evidence that the standard preparticipation physical evaluation is effective in identifying an elevated risk for musculoskeletal injury,[1] nor do standard clinical tests for SRC assessment (eg, standardized assessment of concussion or the Balance Error Scoring System) appear to be sufficiently sensitive to detect subtle changes in perceptual-motor function.[6,10] Despite a clear need for novel clinical approaches for the early detection of residual SRC impairment,[15,26] relatively little research has been focused on the predictive validity of screening methods for identification of individual athletes who possess an elevated risk for repeated SRC or musculoskeletal injury. Because psychological factors appear to influence both the incidence and the severity of SRC, baseline documentation of an athlete's perceived status may be important for guidance of efforts to prevent and clinically manage SRC.[53] Although reported findings from studies of SRC symptoms are inconsistent, white matter integrity has been found to mediate a relationship between the oculomotor function and the number of persisting postconcussion symptoms reported.[52]

Impaired neural activation patterns within and between spatially separated components of brain networks associated with postconcussion symptoms have been documented,[9,10] and the related impairment of cognitive information processing may be responsible for the elevated risk for musculoskeletal injury[19] as well as the risk for a subsequent SRC.[5] A properly designed clinical test of perceptual-motor performance may provide a valuable indirect measurement of neural processing efficiency that does not require the advanced diagnostic equipment and the highly specialized professional expertise necessary for a direct measurement of neural processes.[9,39,48] Impaired performance is most likely to be observed when the cognitive demand imposed by a task exceeds an athlete's capability to recruit additional processing resources, which can be disproportionately manifested among athletes with a history of concussion.[16]

A combination of self-reported persisting effects of SRC and musculoskeletal injuries with an objective measurement of perceptual-motor performance may provide a means to accurately classify an individual athlete's level of injury risk as a component of a preparticipation evaluation process.[33] Thus, the objectives of this study were as follows: (1) to acquire preparticipation data believed to be relevant to injury risk; (2) to document injury occurrences from the first practice session to the end of the football season; and (3) to utilize predictive modeling methods to quantify the relative odds for injury occurrence between player groups with differing preparticipation risk profiles. Specifically, we sought (1) to identify factors that can accurately categorize an individual football player's risk for occurrence of core or lower extremity injury (CLEI), (2) to identify factors that can accurately categorize an individual football player's risk for occurrence of SRC, and (3) to identify factors that have a strong association with a football player's self-reported lifetime history of SRC. We hypothesized that both perceptual-motor performance and self-reported effects of prior injuries would demonstrate meaningful prospective and retrospective associations (ie, odds ratio [OR] lower limit >1) with injury.

METHODS

A combined cohort of 183 American high school (n = 103) and college (n = 80) football players provided electronic survey responses and performed a perceptual-motor task on a smartphone. Data for players who did not participate throughout the subsequent season for any reason other than injury (n = 22) were excluded, leaving 161 football players (87 high school and 74 college) to be included in the analysis (Figure 1). The high school players completed the screening as part of a preparticipation evaluation, which was administered in a sports medicine clinic. Data were acquired from college players, who were all members of the same team, in an athletic strength and conditioning facility. All study procedures were approved by an institutional review board.

The surveys included a Sport Fitness Index (SFI), which documents self-ratings of persisting effects of prior musculoskeletal injuries,[55] and an Overall Wellness Index (OWI), which is designed to document the temporal proximity and the frequency of physical, cognitive, behavioral, sleep-related, and mood disorders associated with postconcussion syndrome (Appendix Figure A1).[54] Responses to 10 items on both the SFI and the OWI were used to generate 0 to 100 scores for each, with low values indicating suboptimal status. Previous research has demonstrated good internal

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Ethical approval for this study was obtained from the University of Tennessee at Chattanooga (No. 16-122, 19-055).

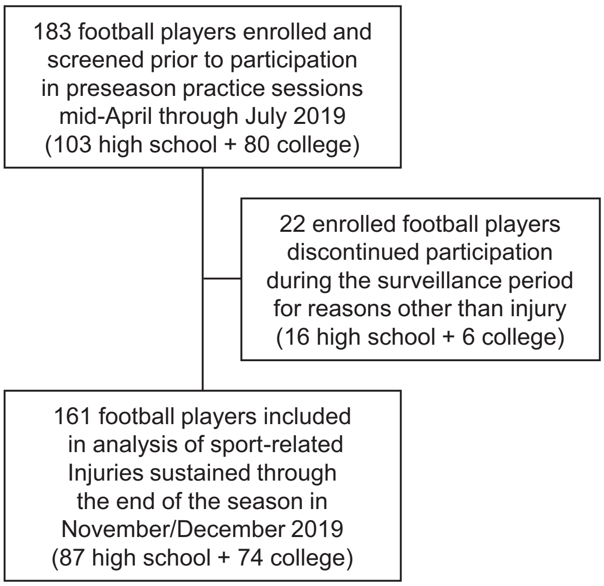

Figure 1. Flowchart of participant enrollment and data included in the analysis.

Figure 2. Smartphone application for the Eriksen flanker test.

consistency for both the SFI score[55] (Cronbach $\alpha = .89$) and the OWI score[54] (Cronbach $\alpha = .82$). The OWI does not make any reference to concussion, but its 10 categories of problems include 82 postconcussion symptoms.[32,52] The number of reported postconcussion symptoms derived from OWI responses was evaluated as another potential predictor variable, which has previously demonstrated strong predictive validity for identification of former athletes with a self-reported history of SRC.[54]

The Eriksen flanker test[57] was administered with an investigational Android smartphone software application (app) that displayed 20 sets of arrow configurations for 300 milliseconds (ms) each (10 incongruent “<<><<” or “>><>>” and 10 congruent “<<<<<” or “>>>>>” in a random order), with variable interstimulus intervals ranging from 500 to 1500 ms (Figure 2). A correct response to the direction indicated by the center arrow was registered by rapid manual tilting of the smartphone in a right or left direction. Previous research[54] has demonstrated good test-retest absolute agreement on different days for both reaction time and response accuracy derived from the app, with intraclass correlation coefficient values of 0.80 for reaction time and 0.70 for response accuracy. Each player completed a familiarization trial that consisted of 10 arrow sets immediately before a single test trial. Metrics derived from reaction time and response accuracy values included inverse efficiency (reaction time divided by response accuracy), inverse efficiency ratio (incongruent inverse efficiency divided by congruent inverse efficiency), and conflict effect (incongruent reaction time minus congruent reaction time).

Injuries sustained during the subsequent season were documented by athletic trainers affiliated with each of the represented football programs. The outcome of primary interest was CLEI, which was defined as “any joint sprain or muscle strain” that required evaluation and resulted in any degree of activity modification, and occurrence of SRC diagnosed by the medical personnel of the football program. A receiver operating characteristic (ROC) analysis was used to assess the prospective association of each variable with the occurrence of CLEI or SRC as well as the association with history of SRC and to convert variables into binary risk categories. The Youden index was used to identify the binary cut point that provided the best balance of sensitivity and specificity for maximum classification accuracy. The OR and its 90% CI were derived from a cross-tabulation analysis to represent the strength of each univariable association.[56]

A logistic regression analysis was used to identify any multifactor model that provided good prospective discrimination, with a minimum 10:1 ratio of injury cases to predictive factors. Competition level (high school vs college) was included as a covariate to assess its possible effect modification. Flanker test metrics were analyzed as both continuous and binary predictor variables. An analysis of credibility was used to assess the potential clinical utility of a predictive model.[34]

To compare group means for any continuous variable found to have a predictive power, any outlier values exceeding 3 standard deviations above the mean for the combined groups were replaced with the value corresponding to 3 standard deviations above the mean before analysis by a 2-tailed independent t test. Group median values for ordinal data derived from survey responses were compared by the Mann-Whitney U test, and the interquartile range was reported for variables that demonstrated a significant difference in median values. An alpha level of .05 defined a statistically significant difference between groups. All statistical analyses were performed by SPSS Version 26 (IBM).

RESULTS

After exclusion of data for 22 players whose participation was terminated for reasons unrelated to injury, the remaining dataset represented 87 high school players from 14

TABLE 1
Prospective Univariable Associations of Preparticipation Measures With Occurrence of Core or Lower Extremity Sprain or Strain[a]

Predictor	AUC	Cut Point, ms	Sensitivity, %	Specificity, %	PPV, %	NPV, %	+LR	–LR	OR (90% CI)
Conflict effect	.561	≥69	50	68	61	58	1.56	0.74	2.12 (1.24-3.62)
History of SRC	–	Yes/No	26	83	60	53	1.52	0.89	1.70 (0.90-3.23)
2-Factor model	.618	≥1 Positive	64	59	61	62	1.57	0.61	2.56 (1.50-4.36)

[a]Dash indicates lack of an AUC value for a binary (Yes/No) variable. AUC, area under curve; +LR, positive likelihood ratio; –LR: negative likelihood ratio; NPV, negative predictive value; OR, odds ratio; PPV, positive predictive value; SRC, sport-related concussion.

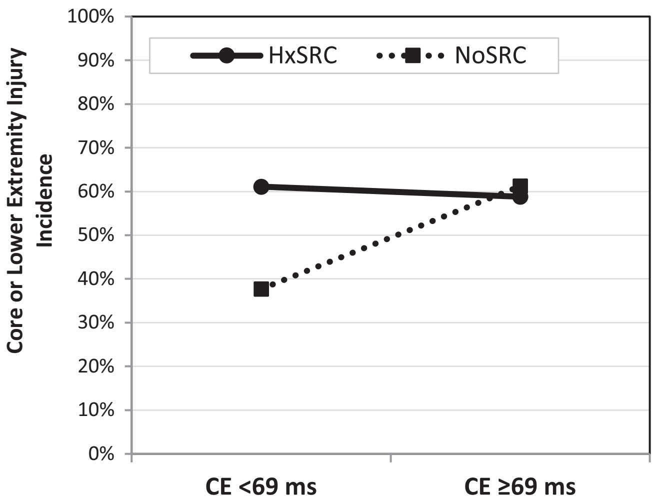

Figure 3. Incidence of CLEI for binary classification of HxSRC versus NoSRC history and the flanker test CE ≥69 ms (prolonged) versus <69 ms (brief). CE, conflict effect; CLEI, core or lower extremity injury; HxSRC, sport-related concussion history; ms, millisecond; NoSRC, no sport-related concussion.

programs (age, 15.6 ± 1.1 years; height, 1.77 ± 0.13 m; weight, 88.93 ± 26.24 kg) and 74 members of 1 college team (age, 20.1 ± 1.5 years; height, 1.85 ± 0.07 m; weight, 103.21 ± 19.42 kg). Two outlier values for reaction time were identified and adjusted. A lifetime history of SRC was reported by 22% of the players (35/161), with 77% (27/35) reporting a single SRC and 23% (8/35) reporting 2 or 3 SRCs. The occurrence of SRC within the previous 12 months was reported by 14% (5/35) of these players. The total number of documented CLEIs was 123 (foot = 9; ankle = 33; lower leg = 11; knee = 35; thigh = 9; hip/groin = 13; low back/abdomen = 13). Among the players who sustained a CLEI, 36% (29/80) sustained ≥2 CLEIs. At least 1 CLEI was sustained by 80 of the 161 players in the cohort (39/87 high school and 41/74 college), with a 60% incidence (21/35) among players with SRC history versus a 47% incidence (59/126) among players with no SRC history.

Although the effect of SRC history on CLEI occurrence was not statistically significant (Table 1), its magnitude (OR, 1.70) exceeded the lower limit of values documented by a previous systematic review and meta-analysis (OR, 1.46).[37] Flanker test conflict effect ≥69 ms was statistically significant as a binary predictor of CLEI occurrence. The lowest incidence of CLEI was 38% (29/77) for players with conflict effect <69 ms and no SRC history (Figure 3). Modeling the conflict effect as a continuous variable with SRC history demonstrated the identical ROC cut point for the predicted probability (constant = –0.317; β for conflict effect = 0.003; β for SRC history = 0.519) as that for binary modeling of the conflict effect with SRC history (constant = –0.411; β for conflict effect ≥69 ms = 0.724; β for SRC history = 0.478). The latter 2-factor model provided discrimination between groups that was both statistically significant ($\chi^2[1] = 8.54$; 2-sided; $P = .003$) and intrinsically credible (OR, 2.56; >95% skepticism limit of 1.79). The outlier analysis identified 2 extreme conflict effect values (1 SRC history and 1 no SRC history) that were adjusted before comparison of group means, which demonstrated a significant difference (conflict effect for history vs no history of SRC, 73 ± 74 vs 47 ± 83 ms; $t_{159} = 2.02$; $P = .039$). A stratified analysis limited to the 35 players with SRC history identified a prospective association with CLEI occurrence for the SFI ≤90 (OR, 9.50; 90% CI, 2.11-42.83), with a 73% (19/26) positive predictive value and a 78% (7/9) negative predictive value.

Factors that discriminated SRC history from no SRC history at baseline included postconcussion symptoms ≥4, the SFI score ≤88, and the OWI score ≤94 (Table 2). The only statistically significant difference in median values was found for SFI scores (history vs no history of SRC: 84 [IQR, 22] vs 92 [IQR, 14]; $U_1 = 6.95$; $P = .008$).

The low 6% (10/161) incidence of SRC occurrence (7/87 high school and 3/74 college) precluded a multivariable logistic regression analysis. Despite the large upper 90% CI limits produced by the small number of SRC events, potentially meaningful univariable associations were observed for the OWI score ≤78, postconcussion symptoms ≥4, the SFI score ≤78, SRC history, and the flanker test inverse efficiency ratio ≥1.7 (Table 3). Among players who sustained a concussion during the surveillance period, 40% (4/10) reported baseline symptoms of headaches, muscle aches, and sleep loss, and 30% (3/10) reported body pains and trouble falling asleep.

DISCUSSION

American football players who exhibited a preparticipation smartphone flanker test conflict effect ≥69 ms or a self-reported lifetime history of SRC were more likely to sustain

TABLE 2
Prospective Univariable Associations of Preparticipation Measures With Occurrence of SRC[a]

Predictor	AUC	Cut Point	Sensitivity, %	Specificity, %	PPV, %	NPV, %	+LR	–LR	OR (90% CI)
Postconcussion symptoms (0-82)	.603	≥4	37	87	45	83	2.93	0.72	4.06 (1.97-8.38)
SFI score (0-100)	.638	≤88	74	58	33	89	1.77	0.44	3.98 (1.97-8.03)
OWI score (0-100)	.582	≤94	63	54	28	84	1.37	0.69	1.98 (1.04-3.79)

[a]AUC, area under curve; +LR, positive likelihood ratio; –LR, negative likelihood ratio; NPV, negative predictive value; OR, odds ratio; OWI, Overall Wellness Index; PPV, positive predictive value; SFI, Sport Fitness Index; SRC, sport-related concussion.

TABLE 3
Retrospective Univariable Associations of Preparticipation Measures With History of SRC[a]

Predictor	AUC	Cut Point	Sensitivity, %	Specificity, %	PPV, %	NPV, %	+LR	–LR	OR (90% CI)
OWI score (0-100)	0.656	≤78	60	87	23	97	4.53	0.46	9.83 (3.17-30.50)
Postconcussion symptoms (0-82)	0.666	≥4	60	85	21	97	3.94	0.47	8.35 (2.71-25.72)
SFI score (0-100)	0.596	≤78	60	78	15	97	2.67	0.52	5.16 (1.70-15.65)
History of SRC	—	Yes/No	50	80	14	96	2.52	0.62	4.03 (1.35-12.03)
Inverse efficacy ratio	0.564	≥1.7	50	76	12	96	2.10	0.66	3.19 (1.08-9.47)

[a]AUC, area under the curve; +LR, positive likelihood ratio; –LR, negative likelihood ratio; NPV, negative predictive value; OR, odds ratio; OWI, Overall Wellness Index; PPV, positive predictive value; SFI, Sport Fitness Index; SRC, sport-related concussion.

a CLEI before the end of the subsequent season. Players who possessed either or both of the risk factors had 2.56 times greater odds for CLEI occurrence compared with those who did not possess either of the risk factors (CLEI incidence of 61% [51/84] vs 38% [29/77]). Although SRC incidence was only 6% (10/161), strong prospective associations were identified with the OWI score ≤78 (OR, 9.83), number of postconcussion symptoms ≥4 (OR, 8.35), the SFI score ≤78 (OR, 5.16), SRC history (OR, 4.03), and the smartphone flanker test inverse efficiency ratio ≥1.7 (OR, 3.19). Retrospective associations with self-reported history of SRC included number of postconcussion symptoms ≥4 (OR, 4.06), the SFI score ≤88 (OR, 3.98), and the OWI score ≤94 (OR, 1.98). Collectively, the study results suggest that smartphone measurements of perceptual-motor efficiency and responses to survey questions about persisting effects of past injuries can provide valuable information for estimation of injury risk among American football players.

Previous injury is widely understood to be the strongest predictor of subsequent injury,[38] but identification of modifiable factors that can be addressed by properly designed interventions is necessary for prevention.[1] No prior studies have established predictors of postconcussion musculoskeletal injury.[6] Previous research has related Eriksen flanker test performance to neural correlates of impaired executive function through functional magnetic resonance imaging,[14,18,39,58] diffusion tensor imaging,[20,43] and electrophysiological testing.[13,41] Several previous studies[13,14,36,48] have identified the conflict effect as a key metric for the assessment of neural processing efficiency. The ≥69-ms cut point we identified as a good predictor of CLEI occurrence closely approximates the conflict effect mean value of 67 ms previously reported for a cohort of 280 college football players.[57] Neural activation patterns evoked by the flanker test have been linked to functional connectivity strength among the default mode, salience, and central executive networks.[29,40] The anterior cingulate cortex is a key node of the salience network, which plays a key role in conflict resolution and speed of accurate responses to stimuli.[48] Thus, metrics derived from our smartphone flanker test app might be considered indirect evidence of impaired functional connectivity within neural circuits that integrate perception, cognition, and execution of motor responses.[46]

The observed relationships among binary variables illustrated in Figure 3 raise a number of questions about CLEI susceptibility. Among football players with prolonged conflict effect (≥69 ms), the incidence of CLEI was 59% (10/17) for those with history of SRC and 61% (30/49) for those classified as having no SRC history. Possible explanations for the latter finding include failure of some players to report history of SRC,[30] effects of subconcussive head impacts sustained during football participation,[22] and individual variability in neural processing of the conflicting stimuli that is unrelated to brain injury.[21] The finding that CLEI incidence for players with history of SRC and relatively small conflict effect (<69 ms) was 61% (11/18) suggests that a factor other than conflict resolution was responsible for elevated injury susceptibility. Among the 35 players with SRC history, the SFI score ≤90 demonstrated a strong prospective association with the occurrence of CLEI (91% sensitivity and 50% specificity). Thus, persistence of functional limitations associated with previous musculoskeletal injuries provides a plausible explanation.

The low 6% (10/161) incidence of SRC occurrence severely limits the inference that can be drawn from the observed associations with preparticipation measures, but they nonetheless provide evidence that may be highly relevant to injury risk assessment. Identical sensitivity of 60% (6/10) was evident for the OWI score ≤78, the SFI score ≤78, and postconcussion symptoms ≥4, with respective specificity values of 87%, 78%, and 85%, suggesting that specific survey response patterns may identify individual players who possess an elevated risk for SRC. Consistent with prior research findings,[4,8] self-reported history of SRC demonstrated a prospective association with SRC occurrence. The results suggest that a flanker test metric derived from the respective reaction time and response accuracy values for incongruent and congruent trials may provide an inverse indicator of neural processing efficiency that is relevant to SRC risk. Dividing reaction time by response accuracy provides an inverse efficiency value that is proportional to the error rate, thereby quantifying the speed-accuracy tradeoff in performance of a choice reaction time task.[49] Because the more cognitively demanding incongruent trials produce a larger inverse efficiency value than the less difficult congruent trials, the inverse efficiency ratio provides a single composite metric to represent overall flanker test performance. The finding that inverse efficiency ratio ≥1.7 was associated with SRC occurrence suggests that the smartphone flanker test app may provide risk screening data that have incremental predictive value when combined with survey data. A dataset containing a much larger number of SRC occurrences will be required to develop and evaluate a multivariate prediction model.

As demonstrated by the prospective associations of preparticipation measures with SRC occurrences, survey responses have the potential to yield greater predictive value than a simple binary classification of history versus no history of SRC. The ROC analysis of the postconcussion symptoms count derived from the list of 82 response options within the OWI, which yielded the identical ≥4 cut point for both history of SRC and SRC occurrence. Furthermore, a previous study[54] that included 10 cases with history of SRC and 10 controls with no SRC identified the same postconcussion symptoms ≥4 cut point for maximum discrimination between the 2 groups (OR, 8; 90% CI, 1.99, 32.20). Both the SFI score ≤88 and the OWI score ≤94 demonstrated associations with SRC history that may have utility for injury risk categorization of players who are reluctant to acknowledge having previously sustained a concussion. As many as two-thirds of college football players may fail to disclose SRC at the time of its occurrence,[30] but they may respond to preparticipation survey questions about functional limitations and general health symptoms in a more truthful manner. Although the OWI survey items were developed to correspond to previously documented postconcussion symptoms,[32,52] such symptoms are common in the general population and are not necessarily attributable to a previous SRC.[2,7,16] Any players whose preparticipation survey response patterns approximate those of individuals who affirm history of SRC could reasonably be assumed to have a similar level of risk for future SRC or CLEI, regardless of whether or not SRC history is truthfully affirmed.

Although the precise mechanism by which SRC elevates the risk for musculoskeletal injury remains unknown,[28] it may result from the same neuroinflammatory process that is believed to increase brain vulnerability to repeated SRC and neurodegeneration.[5,33] Microstructural disruption of connectivity within and between brain networks can variably affect cognition, mood, and motor coordination.[25,45] There is evidence that multimodal neuromuscular control training (ie, postural balance, progressive resistance, plyometric, and functional movement exercises) can substantially reduce the incidence of both SRC and musculoskeletal injuries.[3,27] A plausible mechanism for reduced injury susceptibility is neuroplastic adaptation within neural circuits that integrates perceptual, cognitive, and motor processes, thereby promoting rapid and accurate responses in a rapidly changing sport environment. Although the simple manual response required to perform the smartphone flanker test is far less complex than the multisegmental and multidirectional whole-body movements associated with sport participation, it nonetheless provides a feasible means to quantify perceptual-motor efficiency for injury risk assessment. The follow-up assessment of individual athletes who have a high level of preparticipation injury risk, or those who have recently sustained an injury, could involve perceptual-motor testing both before and after a moderate to vigorous exercise session. Recent research findings suggest that physical activity can improve cognitive task efficiency among healthy individuals, whereas performance may be worsened among those who have recently sustained a concussion[51] as well as those with a remote history of SRC.[54]

Our study is not without limitations that should be considered for proper interpretation of our findings. Reliance on self-reported history of SRC can certainly be viewed as a study limitation, but any misclassifications of players as having no SRC history would be more likely to decrease the strength of the reported associations than to increase them. Other study limitations included a lack of exposure data for calculation of incidence rates and an insufficient cohort size to perform stratified analyses for the assessment of other possible confounding factors, such as time elapsed since the most recent SRC, number of previous SRCs, psychological profile, diagnosis of attention-deficit/hyperactivity disorder, and any prescribed medications. Because there were only 10 SRC occurrences during the surveillance period, the precision of the estimated prospective associations was far from optimal. ROC area under curve values were relatively small, which is not uncommon for prognostic studies that involve surveillance for injury occurrence. Despite these limitations, our findings strongly suggest that the combination of perceptual-motor performance metrics and survey responses can identify individual high school and college football players who are likely to derive benefit from interventions designed to address specific injury risk factors. Further research is needed to assess prediction model calibration and to externally validate its accuracy in other cohorts.

CONCLUSION

Our findings support the combination of quantifiable survey responses with measures of perceptual-motor performance to classify an athlete's level of injury risk. The potential for a multimodal training program to reduce the risk for both SRC and musculoskeletal injury has been documented. Our screening methods offer a means to identify a subset of athletes who would be most likely to derive benefit from an injury risk reduction intervention.

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APPENDIX

Physical Problems
□ Headaches
□ Pressure in head
□ Neck pain
□ Muscle aches
□ Nausea/vomiting
□ Light sensitivity
□ Noise sensitivity
□ Joint aches
□ Urinary incontinence
□ Bowel incontinence
□ General discomfort

Sleep/Stamina Problems
□ Sleeping less
□ Sleeping more
□ Trouble falling asleep
□ Fatigue/lethargy
□ Drowsiness
□ Feeling slowed down

Muscle Control Problems
□ Muscle weakness
□ Involuntary movements
□ Muscle twitching
□ Muscle jerking
□ Difficulty walking
□ Tremor (oscillating motions)
□ Changed handwriting
□ Trouble using tools
□ Difficulty using hands or feet
□ Trouble swallowing

Balance/Orientation Problems
□ Postural swaying/falling
□ Spinning sensations
□ Dizziness
□ Lost in familiar environment
□ Trouble seeing things properly
□ Difficulty recognizing faces
□ Impaired perception of objects

Altered Sensations
□ Vision changes
□ Tingling
□ Numbness
□ Body pains
□ Other changed sensations

Mood/Emotional Problems
□ Suppression of emotions
□ Emotional instability
□ Depression/sadness
□ Anxiety
□ Nervousness
□ Irritability

Behavior Control
□ Apathy/lack of motivation
□ Loss of inhibitions
□ Intense spirituality
□ Delusions
□ Personality changes
□ Agitation/aggression
□ Violent outbursts
□ Obsession/compulsion
□ Repetitive behaviors
□ Criminal behavior
□ Impaired hygiene
□ Altered eating habits
□ Hallucinations

Memory-Related Problems
□ Misplaced objects
□ Asking questions repetitively
□ Missed appointments
□ Difficulty remembering past events

Thinking-Related Problems
□ Planning/organizing difficulty
□ Multi-tasking difficulty
□ Problem-solving difficulty
□ Mental rigidity (inflexibility)
□ Impulsive responses
□ Mental fogginess
□ Difficulty concentrating
□ Bad decisions
□ Confusion

Language-Related Problems
□ Impaired writing
□ Impaired spelling
□ Impaired reading
□ Trouble choosing words
□ Slurred speech, difficulty articulating words
□ Stuttering
□ Incorrect word use/mispronunciation
□ Increased speech output
□ Impaired language comprehension
□ Decreased speech output
□ Impaired word comprehension

Figure A1. Overall Wellness Index: 10 categories of 82 postconcussion symptoms. Adapted from Wilkerson et al.[54]