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

Gary B. Wilkerson,*† EdD, ATC, Jeremy R. Bruce,‡ MD, Andrew W. Wilson,† MS, ATC, Neal Huang,‡ MD, Mina Sartipi,§ PhD, Shellie N. Acocello,† PhD, ATC, Jennifer A. Hogg,† PhD, ATC, and Misagh Mansouri,§ PhD

Investigation performed at the University of Tennessee at Chattanooga, Chattanooga, Tennessee, USA

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 studies19,23,37 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 function24; 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
neuroinflammatory response within the brain\textsuperscript{33,50} and further elevate the risk for lower extremity injury.\textsuperscript{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.\textsuperscript{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,\textsuperscript{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.\textsuperscript{6,10} Despite a clear need for novel clinical approaches for the early detection of residual SRC impairment,\textsuperscript{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.\textsuperscript{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 post-concussion symptoms reported.\textsuperscript{52}

Impaired neural activation patterns within and between spatially separated components of brain networks associated with postconcussion symptoms have been documented\textsuperscript{9,10} and the related impairment of cognitive information processing may be responsible for the elevated risk for musculoskeletal injury\textsuperscript{19} as well as the risk for a subsequent SRC.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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\textsuperscript{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).\textsuperscript{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

---

\textsuperscript{1}Address correspondence to Gary B. Wilkerson, EdD, ATC, Department of Health and Human Performance, University of Tennessee at Chattanooga, Chattanooga, TN 37403, USA (email: Gary-Wilkerson@utc.edu).

\textsuperscript{2}Department of Health and Human Performance, University of Tennessee at Chattanooga, Chattanooga, Tennessee, USA.

\textsuperscript{3}Department of Orthopaedic Surgery, University of Tennessee College of Medicine, Chattanooga, Tennessee, USA.

\textsuperscript{4}Center for Urban Informatics and Progress, University of Tennessee at Chattanooga, Chattanooga, Tennessee, USA.

Final revision submitted June 7, 2021; accepted August 4, 2021.

One or more of the authors has declared the following potential conflict of interest or source of funding: This study was supported by a Biomedical Research Initiation Collaborative Grant, which was internally funded by the University of Tennessee College of Medicine, the University of Tennessee Health Science Center, Erlanger Health System, and the University of Tennessee at Chattanooga. J.R.B. has received education payments from Alpha Orthopedic Systems; nonconsulting fees from Abbott Laboratories; and hospitality payments from Arthrex and Smith & Nephew. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval for this study was obtained from the University of Tennessee at Chattanooga (No. 16-122, 19-055).
consistency for both the SFI score (Cronbach $\alpha = .89$) and the OWI score (Cronbach $\alpha = .82$). The OWI does not make any reference to concussion, but its 10 categories of problems include 82 postconcussion symptoms. 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.

The Eriksen flanker test 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 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.

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.

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 football programs enrolled and screened prior to participation in preseason practice sessions mid-April through July 2019 (103 high school + 80 college)
TABLE 1
Prospective Univariable Associations of Preparticipation Measures With Occurrence of Core or Lower Extremity Sprain or Strain*

| 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) |

*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.

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 ≤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]; 𝑈150 = 6.95; 𝑃 = 0.008).

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 ≤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]; 𝑈150 = 6.95; 𝑃 = 0.008).

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 ≤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]; 𝑈150 = 6.95; 𝑃 = 0.008).

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]; 𝑈150 = 6.95; 𝑃 = 0.008).

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 ≤88, 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 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 (χ²(1) = 8.54; 2-sided; 𝑃 = 0.003) 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; 𝑇150 = 2.02; 𝑃 = 0.039). 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.
Previous research has related prior studies have established predictors of postconcussion impaired executive function through functional magnetic studies have identified the conflict effect as a key metric for the assessment of neural processing efficiency. The mean value of 67 ms previously reported for a cohort of 280 college football players. Neural activation patterns evoked by the flanker test have been linked to functional connectivity strength among the default mode, salience, and central executive networks. 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. 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.

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; effects of subconcussive head impacts sustained during football participation, and individual variability in neural processing of the conflicting stimuli that is unrelated to brain injury. 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

### TABLE 2
Prospective Univariable Associations of Preparticipation Measures With Occurrence of SRC

| 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) |

*aAUC, 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

| 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       | 70             | 78             | 15     | 97     | 2.67   | 0.52   | 5.16 (1.70-15.65) |
| History of SRC                              |      | Yes/No    | 50             | 80             | 14     | 98     | 2.52   | 0.62   | 4.03 (1.35-12.03) |
| Inverse efficacy ratio                      | 0.564| ≥1.7      | 50             | 76             | 12     | 98     | 2.10   | 0.66   | 3.19 (1.08-9.47) |

*aAUC, 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.

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, but identification of modifiable factors that can be addressed by properly designed interventions is necessary for prevention. No prior studies have established predictors of postconcussion musculoskeletal injury. Previous research has related Eriksen flanker test performance to neural correlates of impaired executive function through functional magnetic resonance imaging, diffusion tensor imaging, and electrophysiological testing. Several previous studies 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...
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, 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. 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 that included 10 cases with history of SRC and 10 controls with no SRC demonstrated a similar 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, 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, such symptoms are common in the general population and are not necessarily attributable to a previous SRC. 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, it may result from the same neuroinflammatory process that is believed to increase brain vulnerability to repeated SRC and neurodegeneration. Microstructural disruption of connectivity within and between brain networks can variably affect cognition, mood, and motor coordination. 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. 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 as well as those with a remote history of SRC.

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.

ACKNOWLEDGMENT
The authors appreciate the contributions of Britteny Wilson MS, ATC, and Megan Dishman, MS, ATC, who provided valuable assistance in acquisition of the study data.

REFERENCES
1. Anduvo FD, Fletcher IE, McGrew C. Musculoskeletal preparticipation physical evaluation—does it lead to decreased musculoskeletal morbidity? Curr Sports Med Rep. 2020;19(2):58-69.
2. Askern BM, Snyder AR, Clugston JR, Gaynor LS, Sullan MJ, Bauer RM. Concussion-like symptom reporting in non-concussed collegiate athletes. Arch Clin Neuropsychol. 2017;32(8):963-971.
3. Atwood MJ, Roberts SP, Trewartha G, England ME, Stokes KA. Efficiency of a movement control injury prevention programme in adult men’s community rugby union: a cluster randomised controlled trial. Br J Sports Med. 2018;52(6):368-374.
4. Brett BL, Kuhn AW, Yengo-Kahn AM, Solomon GS, Zuckerman SL. Risk factors associated with sustaining a sport-related concussion: an initial synthesis study of 12,320 student-athletes. Arch Clin Neuropsychol. 2018;33(8):984-992.
5. Brett BL, Wu Y-C, Mustafi SM, et al. The association between persistent white-matter abnormalities and repeat injury after sport-related concussion. Front Neurol. 2020;10(1345):1345. doi:10.3389/fneur.2019.01345.
6. Buckley TA, Howard CM, Oldham JR, Lynall RC, Swanik CB, Getchell N. No clinical predictors of postconcussion musculoskeletal injury in college athletes. Med Sci Sports Exerc. 2020;52(6):1256-1262.
7. Cassidy JD, Cancelliere C, Carroll LJ, et al. Systematic review of self-reported prognosis in adults after mild traumatic brain injury: results of the International Collaboration on Mild Traumatic Brain Injury Prognosis. Arch Phys Med Rehabil. 2014;95(3):S132-S151.
8. Castellanos J, Phoo CP, Eckner JT, et al. Predicting risk of sport-related concussion in collegiate athletes and military cadets: a machine learning approach using baseline data from the CARE Consortium Study. Sports Med. 2021;51(3):567-569.
9. Churchill NW, Hutchison MG, Graham SJ, Schweizer TA. Brain function associated with reaction time after sport-related concussion. Brain Imaging Behav.2021;5(3):1508-1517.
10. Churchill NW, Hutchison MG, Graham SJ, Schweizer TA. Connectomic markers of symptom severity in sport-related concussion: whole-brain analysis of resting-state fMRI. Neuroimage Clin. 2018;18:518-526.
11. Churchill NW, Hutchison MG, Graham SJ, Schweizer TA. Mapping brain recovery after concussion: from acute injury to 1 year after medical clearance. Neurology. 2019;93(21):e1980-e1992.
12. Churchill NW, Hutchison MG, Richards D, Leung G, Graham SJ, Schweizer TA. Neuroimaging of sport concussion: persistent alterations in brain structure and function at medical clearance. Sci Rep. 2017;7(1):8297. doi:10.1038/s41598-017-07742-41593.
13. De Beaumont L, Theoret H, Mongeon D, et al. Brain function decline in healthy retired athletes who sustained their last sports concussion in early adulthood. Brain. 2009;132(3):695-708.
14. Erickson KL, Ho M-HR, Colcombe SJ, Kramer AF. A structural equation modeling analysis of attentional control: an event-related fMRI study. Brain Res Cogn Brain Res. 2005;22(3):349-357.
15. Ettenhofer ML, Barry DM. Saccadic impairment associated with remote history of mild traumatic brain injury. J Neuropsychiatry Clin Neurosci. 2016;28(3):223-231.
16. Ettenhofer ML, Hershaw JN, Engle JR, Hungerford LD. Saccadic impairment in chronic traumatic brain injury: examining the influence of cognitive load and injury severity. Brain Inj. 2018;32(13-14):1740-1748.
17. Ezza HSA, Khadrawy YA. Glutamate excitotoxicity and neurodegeneration. J Mol Genet Med. 2014;8(4). doi:10.4172/1747-0862.1000141.
18. Fan J, McCandliss BD, Fossella J, Flombaum JI, Posner MI. The activation of attentional networks. Neuroimage. 2005;26(2):471-479.
19. Fino PC, Becker LN, Fino NF, Griesemer B, Goforth M, Brolinson PG. Effects of recent concussion and injury history on instantaneous relative risk of lower extremity injury in Division I collegiate athletes. Clin J Sport Med. 2017;27(3):218-223.
20. Fitzgerald DB, Crosson BA. Diffusion weighted imaging and neuro-psychological correlates in adults with mild traumatic brain injury. Int J Psychophysiol. 2011;82(1):79-85.
21. Fjell AM, Westlye LT, Amlien IK, Waalhovi KB. Reduced white matter integrity is related to cognitive instability. J Neurosci. 2011;31(49):18060-18072.
22. Foss KDB, Yuan W, Diekuffs JA, et al. Relative head impact exposure and brain white matter alterations after a single season of competitive football: a pilot comparison of youth versus high school football. Clin J Sport Med. 2019;29(6):442-450.
23. Harada GK, Rugg CM, Arshi A, Vail J, Hame SL. Multiple concussions increase odds and rate of lower extremity injury in National Collegiate Athletic Association athletes after return to play. Am J Sports Med. 2019;47(13):3256-3262.
24. Harmon KG, Clugston JR, Dec K, et al. American Medical Society for Sports Medicine position statement on concussion in sport. Br J Sports Med. 2019;53(4):213-225.
25. Hellawell SC, Welton T, Pearce AJ, Maller JJ, Grieve SM. Diffusion MRI as a complementary assessment to cognition, emotion, and motor dysfunction after sports-related concussion: a systematic review and critical appraisal of the literature. Brain Imaging Behav. 2021;15(3):1685-1704.
26. Hirad AA, Bazarian JJ, Merchant-Borna K, et al. A common neural signature of brain injury in concussion and subconcussion. Sci Adv. 2019;5(8):eaau3460. doi:10.1126/sciadv.aau3460.
27. Hislop MD, Stokes KA, Williams S, et al. Reducing musculoskeletal injury and concussion risk in schoolboy rugby players with a pre-activity movement control exercise programme: a cluster randomised controlled trial. Br J Sports Med. 2017;51(5):1140-1146.
28. Howell DR, Lynall RC, Buckley TA, Herman DC. Neuromuscular control deficits and the risk of subsequent injury after a concussion: a scoping review. Sports Med. 2018;48(5):1097-1115.
29. Kelly AC, Uddin LD, Biswal BB, Castellanos FX, Milham MP. Competition between functional brain networks mediates behavioral variability. Neuroimage. 2008;39(1):527-537.
30. Kerr ZY, Register-Mihalik JK, Kroshus E, Baugh CM, Marshall SW. Motivations associated with nondisclosure of self-reported concussions in former collegiate athletes. Am J Sports Med. 2016;44(1):220-225.
31. Kerr ZY, Wilkerson GB, Caswell SV, et al. The first decade of web-based sports injury surveillance: descriptive epidemiology of injuries in United States high school football (2005–2006 through 2013–2014) and National Collegiate Athletic Association football (2004–2005 through 2013–2014). J Athl Train. 2018;53(8):738-751.
32. Kontos AP, Elbin R, Schatz P, et al. A revised factor structure for the post-concussion symptom scale: baseline and postconcussion factors. Am J Sports Med. 2012;40(10):2375-2384.

33. Ledneux A, Pyrhopd MK, Gorgens K, et al. Assessment of long-term effects of sports-related concussions: biological mechanisms and exosomal biomarkers. Front Neurosci. 2020;14:761. doi:10.3389/fnins.2020.00761

34. Matthews RA. Moving towards the post p < 0.05 era via the analysis of credibility. Am Stat. 2019;73(1):202-212.

35. McAllister T, McCrea M. Long-term cognitive and neuropsychiatric consequences of repetitive concussion and head-impact exposure. J Athl Train. 2017;52(3):309-317.

36. McGowan AL, Breizin AC, Savage JL, Petit KM, Covassin T, Pontifex MB. Acute and protracted disruptions to inhibitory control following sports-related concussion. Neuropsychologia. 2019;131:223-232.

37. McPherson AL, Nagai T, Webster KE, Hewett TE. Musculoskeletal injury risk after sport-related concussion: a systematic review and meta-analysis. Am J Sports Med. 2018;47(7):1754-1762.

38. Meeuwisse WH, Tyerman H, Hagel B, Emery C. A dynamic model of etiology in sport injury: the recursive nature of risk and causation. Clin J Sport Med. 2007;17(3):215-219.

39. Mennes M, Kelly C, Zuo X-N, et al. Inter-individual differences in resting-state functional connectivity predict task-induced BOLD activity. Neuroimage. 2010;50(4):1690-1701.

40. Mennes M, Zuo X-N, Kelly C, et al. Linking inter-individual differences in neural activation and behavior to intrinsic brain dynamics. Neuroimage. 2011;54(4):2950-2959.

41. Moore RD, Hillman CH, Broglio SP. The persistent influence of cognitive reaction time: a 3 T diffusion tensor imaging study of mild traumatic brain injury. AJNR Am J Neuroradiol. 2008;29(5):967-973.

42. Nordström A, Nordström P, Ekstrand J. Sports-related concussion increases the risk of subsequent injury by about 50% in elite male football players. Br J Sports Med. 2014;48(19):1447-1450.

43. Ozelins B, Aimers N, Parrington L, Pearce AJ. Movement disorders and motor impairments following repeated head trauma: a systematic review of the literature 1990-2015. Brain Inj. 2016;30(8):937-947.

44. Parasuraman R, Jiang Y. Individual differences in cognition, affect, and performance: behavioral, neuroimaging, and molecular genetic approaches. Neuroimage. 2012;59(1):70-82.

45. Perry DC, Sturm VE, Peterson MJ, et al. Association of traumatic brain injury with subsequent neurological and psychiatric disease: a meta-analysis. J Neurosurg. 2016;124(2):511-526.

46. Pontifex MB, O’Connor PM, Broglio SP, Hillman CH. The association between mild traumatic brain injury history and cognitive control. Neuropsychologia. 2009;47(14):3210-3216.

47. Rach S, Diederich A, Colonius H. On quantifying multisensory interaction effects in reaction time and detection rate. Psychol Res. 2011;75(2):77-94.

48. Shahim P, Tegner Y, Marklund N, et al. Astroglial activation and altered amyloid metabolism in human repetitive concussion. Neurol. 2017;88(15):1400-1407.

49. Sicard V, Lortie J-C, Moore RD, Ellemberg D. Cognitive testing and exercise to assess the readiness to return to play after a concussion. Trans J Am Coll Sports Med. 2020;5(11):1-9. doi:10.1249/TJX.0000000000000130

50. Taghdiri F, Chung J, Irwin S, et al. Decreased number of self-paced saccades in post-concussion syndrome associated with higher symptom burden and reduced white matter integrity. J Neurotrauma. 2018;35(5):719-729.

51. Trinh LN, Brown SM, Mulcahey MK. The influence of psychological factors on the incidence and severity of sports-related concussions: a systematic review. Am J Sports Med. 2019;48(6):1516-1525.

52. Wilkerson GB, Acocello SN, Davis MB, Ramos JM, Rucker AJ, Hogg JA. Wellness survey responses and smartphone app response efficiency: associations with remote history of sport-related concussion. Percept Mot Skills. 2021;128(2):714-730.

53. Wilkerson GB, Colston MA, Baker CS. A sport fitness index for assessment of sport-related injury risk. Clin J Sport Med. 2016;26(5):423-428.

54. Wilkinson M. Distinguishing between statistical significance and practical/clinical meaningfulness using statistical inference. Sports Med. 2014;44(3):295-301.

55. Wylie SA, Bashore TR, Van Wouwe NC, et al. Exposing an “intangible” cognitive skill among collegiate football players: enhanced interference control. Front Psychol. 2018;9:49. doi:10.3389/fpsyg.2018.00049

56. Zhu DC, Zacks RT, Slade JM. Brain activation during interference resolution in young and older adults: an fMRI study. Neuroimage. 2010;50(2):810-817.
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

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

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

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

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

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

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

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

Sleep/Stamina Problems
- Body pains
- Difficulty concentrating
- Bad decisions
- Confusion

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