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Smartphone Application to Quantify Sport-Related Injury Risk of Individual Athletes

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Smartphone Perceptual-Motor Test Metrics and Survey Responses Identify High School Football Players with Elevated Injury Risk

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Abstract

Context: Following sport-related concussion (SRC), risk for musculoskeletal injury may be approximately 2 times greater, and risk for another SRC may be 3 to 5 times greater. Pre-participation screening methods are needed that can accurately identify athletes who possess elevated injury risk. **Methods:** Occurrences of SRC and core or lower extremity injury (CLEI) were documented throughout a high school football season for a cohort of 92 players who performed a pre-participation perceptual-motor test and provided survey responses. A smartphone flanker test app presented displays of incongruent (<<><< or >><>>) or congruent (<<<<< or >>>>>) arrows arrows that required determination of a right versus left manual tilt of the device to register a response. Reaction time and response accuracy measures were used to derive conflict effect (CE), inverse efficiency index (IEI), and inverse efficiency ratio (IER) metrics. Any post-concussion symptoms (Sx) were quantified by the Overall Wellness Index (OWI) and any persisting effects of previous musculoskeletal injuries were quantified by the Sport Fitness Index (SFI). **Results:** History of SRC (HxSRC) was reported by 15% of the players. Factors that provided strongest discrimination of HxSRC cases from players who denied such history (NoSRC) were OWI Sx ≥4 and CE ≥52, and, with OR=13.9 for both versus 0 or 1 positive. Prospective predictors of CLEI among players with HxSRC included SFI score ≤92 (OR=33.8), IER ≥2.0 (OR=17), and OWI Sx ≥3 (OR=15). Prospective predictors of SRC for the full cohort included OWI Sx ≥7 (OR=36.4), SFI score ≤78 (OR=16.8), OWI score ≤76 (OR=12.8), HxSRC (OR=10), and IER ≥1.7 (OR=3.8). **Conclusion:** Our results suggest the combination of OWI and SFI survey responses with perceptual-motor performance metrics derived from the smartphone flanker test provides an effective means for pre-participation identification of high school football players who possess elevated risk for subsequent SRC or CLEI occurrence.

Word Count: 300 words

Introduction

Recent studies have produced convincing evidence that musculoskeletal injury incidence increases after a sport-related concussion (SRC) has been sustained.[1-3] Risk for musculoskeletal (MSK) injury following SRC appears to be about 2 times greater,[3] and risk for another SRC may be as much as 3-5 times greater.[4] An additional concern is evidence from advanced diagnostic testing procedures that SRC often produces microstructural disruption within white matter tracts that may increase susceptibility to psychiatric and neurodegenerative conditions.[5-7] Current clinical guidelines for return to sport activity after SRC clearly reflect an assumption that resolution of acute symptoms corresponds to restoration of normal brain function,[8] but a growing body of research evidence suggests that an asymptomatic neuroinflammatory process can persist for months or years.[9-11] 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.[12] Repetitive SRC has the potential to exacerbate a chronic neuroinflammatory response within the brain,[13] and further elevate risk for lower extremity injury.[2]

A recent review of literature found no convincing evidence the standard pre-participation physical evaluation (PPE) is effective for identification of elevated risk for MSK injury,[14] and standard clinical tests for SRC assessment (e.g. Standardized Assessment of Concussion and Balance Error Scoring System) do not appear to be sufficiently sensitive to detect subtle changes in cognition and visual-motor function.[15] Despite a clear need for novel clinical approaches to early detection of residual SRC impairment,[16,17] relatively little research has focused on the predictive validity of screening methods for identification of individual athletes who possess elevated risk for repeat SRC or MSK injury. Because psychological factors appear to influence both the incidence and severity of SRC, baseline documentation of an athlete's perceived status may be importance for guidance of efforts to prevent and clinically manage SRC.[18] Although reported findings from studies of symptoms from SRC are inconsistent, direct assessment of white matter integrity has been found to mediate a relationship between oculomotor function and number of persisting post-concussion symptoms.[19]

Impaired functional connectivity within and between spatially separated components of brain networks associated with post-concussion symptoms has been documented,[15] and related impairment of cognitive information processing may be responsible for elevation of risk for MSK injury,[1] as well as risk for another SRC.[12] Direct measurement of brain connectivity requires advanced diagnostic equipment and highly specialized professional expertise, but a properly designed clinical test of perceptual-motor performance may provide a valuable indirect measurement of neural processing efficiency. 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.[20] A combination of self-reported persisting effects of SRC and MSK injuries with an objective measurement of perceptual-motor performance may provide a means to efficiently classify an individual athlete's level of injury risk as a component of a PPE process. Thus, the purposes of this study were to assess retrospective associations of survey responses and perceptual-motor performance metrics with injury history among high school football players, as well as prospective associations with injury occurrence during participation in high school football practice sessions and games for an entire season.

Methods

A cohort of 107 high school football players from 16 different programs (15.6 ± 1.1 years of age; range 13 – 18) provided electronic survey responses and performed a simple perceptual-motor task on a smartphone during a PPE administered in a sports medicine clinic. Informed consent was obtained from each participant and all procedures were approved by the institutional review board of the University of Tennessee at Chattanooga. The electronic surveys included the Sport Fitness Index (SFI), which documents self-ratings of persisting effects of prior musculoskeletal injuries, and the Overall Wellness Index (OWI), which is designed to document the temporal proximity and frequency of physical, cognitive, behavioral, sleep-related, and mood disorders. Responses to 10 items on both the SFI and OWI were used to generate 0-100 scores for each, with low values indicating suboptimal status. The OWI does not make any reference to concussion, but its 10 categories of problems include 82 symptoms (Sx) associated

with persistent concussion effects.[19,21] Number of reported OWI Sx was evaluated as another potential predictor variable.

An Android smartphone app was used to administer the Eriksen flanker test (FT). The app presented 20 5-arrow displays (10 incongruent: <<><< or >><>> and 10 congruent: <<<<< or >>>>>) of 300 ms each, with variable inter-stimulus intervals ranging from 500 to 1500 ms. 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. A familiarization trial consisting of 10 5-arrow displays was conducted immediately prior to a single test trial. Metrics derived from the FT app included average reaction time (RT) for all 20 of the responses, response accuracy (RA), inverse efficiency index (IEI: RT divided by RA), incongruent RT (IncRT), congruent RT (ConRT), IE ratio (IER: incongruent IEI divided by congruent IEI), and conflict effect (CE; i.e. IncRT minus ConRT).

Musculoskeletal injuries sustained during the prior 12-month period and history of sport-related concussion at any time in the past were self-reported through responses entered into an injury inventory section of the electronic SFI survey. Injuries sustained during the subsequent football season were documented by athletic trainers affiliated with the sports medicine program that provided the PPE. Outcomes of primary interest were core or lower extremity injury (CLEI), which was defined as any sprain or strain that required evaluation and resulted in any degree of activity modification, and occurrence of a concussion diagnosed by the football program's medical personnel. Receiver operating characteristic analysis was used to assess the association of each continuous variable with HxSRC, 12-month history of CLEI (HxCLEI), CLEI occurrence, and SRC occurrence, and to convert those that demonstrated a prominent cut-point into binary variables. An odds ratio (OR) was derived from cross-tabulation analysis to represent the strength of a univariable association. A significant association was defined as a 90% confidence interval (CI) lower limit >1.0 for the OR. For cases of perfect classification, the OR was estimated (Est OR) by adding 0.5 to the value in each 2 X 2 cross-tabulation cell. Backward stepwise logistic regression analysis was used to identify a multivariable model that provided the greatest discriminatory power, with an adjusted OR (Adj OR) reported for each binary predictor variable included in the model. To facilitate

interpretation of alternative classifications, positive predictive value (PPV) and negative predictive value (NPV) were reported. Stratified analyses were subsequently conducted to assess associations within cohort subgroups.

Results

Data for 15 players whose participation was terminated for non-medical reasons before end of the football season were excluded from the analysis, which reduced the cohort to 92 players from 14 different programs. A history of SRC (HxSRC) was reported by 15% of the players (14/92), with 79% (11/14) reporting a single SRC and 21% (3/14) reporting 2 or 3 SRCs. Occurrence of SRC within the previous 12 months was reported by 29% (4/14) of the players. Factors that discriminated HxSRC cases from players who denied such a history (NoSRC) included OWI reported symptoms (Sx) ≥4 (OR=8.75; 90% CI: 2.99, 25.57), OWI score ≤88 (OR, 4.78; 90% CI,: 1.78, 12.96), App CE ≥52 ms (OR=3.86; 90% CI: 1.24, 12.00), and SFI score ≤78 (OR=3.38; 90% CI: 1.17, 9.79). Backward stepwise logistic regression retained OWI Sx ≥4 (Adj OR=10.87; 90% CI: 3.35, 35.23) and CE ≥52 ms (Adj OR=5.04; 90% CI: 1.43, 17.83) and as the strongest factors (model P<.001; Hosmer & Lemeshoew goodness-of-fit P=.973; Nagelkerke R2=.281). The 2-factor model ROC demonstrated AUC=.769 for 0, 1, or 2 positive factors. Discrimination between HxSRC and NoSRC for 2 positive versus 1 or 0 positive had 63% PPV and 89% NPV (OR=13.90; 90% CI: 3.66, 52.73) and for 1 or 2 positive versus 0 positive had 23% PPV and 97% NPV (OR=10.58; 90% CI: 1.84, 60.74).

A total of 64 CLEIs were sustained during the season, with at least 1 CLEI sustained by 43% of the players (40/92). A weak association of HxSRC was found with HxCLEI within the previous 12 months (OR=2.15; 90% CI: 0.77, 6.01), but no prospective association of HxSRC with CLEI occurrence was evident from analysis of data for the full cohort (OR=0.97). A stratified analysis limited to the 14 players with HxSRC identified strong prospective associations with CLEI occurrence for SFI ≤92 (Est OR=33.80; 90% CI: 2.26, ∞), App IER ≥2.0 (Est OR=17.00; 90% CI: 1.15, ∞), and OWI Sx ≥3 (OR=15.00; 90% CI: 1.59, 141.93). Among the 14 players with HxSRC, having both SFI ≤92 and IER ≥2.0 demonstrated 100% PPV for CLEI occurrence, and having neither of these factors positive (SFI >92 and IER <2.0) demonstrated 100% NPV.

An 8% (7/92) incidence of SRC occurrence precluded logistic regression analysis for derivation of a multivariable prediction model. Despite large confidence interval upper limits produced by the small number of SRC events, moderate to very strong associations were observed with App IER ≥1.7 (OR=3.83; 90% CI: 1.02, 14.30), HxSRC (OR=10.00; 90% CI: 2.53, 39.47), OWI score ≤76 (OR=12.83; 90% CI: 3.17, 51.89), SFI score ≤78 (OR=16.82; 90% CI: 3.85, 73.53), and OWI Sx ≥7 (OR=36.44; 90% CI: 7.47, 177.87).

Discussion

Previous injury is widely understood to the strongest predictor of subsequent injury,[22] but the potential for injury prevention requires identification of modifiable factors that can be addressed by properly designed interventions.[14] Our FT App results may have identified important indirect indicators of impaired functional connectivity within neural circuits that integrate visual inputs, decision-making, and motor responses. Previous research has related Eriksen FT performance to neural correlates of impaired executive function through functional magnetic resonance imaging,[23-26] diffusion tensor imaging,[27,28] and electrophysiological testing.29,30 Several previous studies have specifically identified CE as a key metric for assessment of neural processing efficiency,[23,30-32] which we found discriminated players with HxSRC from those with NoSRC with a cut point of ≥52 ms.

The App metric that demonstrated the strongest prospective association with CLEI occurrence among players with HxSRC was derived from the respective IEI values for incongruent and congruent FT trials. Dividing RT by RA inflates the RT value in proportion to the error rate, which provides a single value to represent the speed-accuracy tradeoff in performance of a choice RT task.[33] Because white matter lesions associated with behavioral impulsivity can also produce fast and inaccurate responses to visual stimuli,[34] the IEI metric may be a more sensitive indicator of impairment than separate measures of RT and RA. The more cognitively demanding incongruent trials could logically be expected to produce a larger IEI value than that for the less difficult congruent trials. Thus, the ratio of the respective IEI values could provide another unique derived metric for assessment of neural processing efficiency. The IER was found to prospectively associate with injury occurrence, which had cut points of ≥2.0 for CLEI and ≥1.7 for SRC.

The athletes' OWI survey responses provided strong discrimination between HxSRC and NoSRC, and both SFI and OWI responses demonstrated strong prospective associations with the occurrence of SRC. Although the OWI survey items were derived from previously documented post-concussion symptoms,[19,21] such symptoms are common in the general population and are not necessarily attributable to a previous SRC.[20,35,36] Because symptoms associated with post-concussion syndrome appear to be common to all injuries, the term "post-traumatic symptoms" has been suggested as an alternative designation.[35] Athletes who report such symptoms may derive benefit from clinical intervention, regardless of confirmation or denial of HxSRC.[36] Our observed prospective association of SFI responses with SRC occurrence suggests that persisting effects of previous MSK injuries have relevance to head injury susceptibility. An aggressive approach to competition could explain the observed association,[2,37] but any athletes who report post-traumatic symptoms of any origin may benefit from a biopsychosocial model of clinical management.[36]

Important factors that may have affected the strength of our results include the possibility that some players did not accurately report HxSRC and the possibility that repetitive head impacts produced symptoms without SRC having been sustained or diagnosed. In either case, the magnitudes of PPV, NPV, and OR values we report for prospective HxSRC associations with CLEI and SRC could be underestimates of true values. Limitations included a lack of exposure data for calculation of incidence rates and an insufficient cohort size to perform stratified analyses for assessment of other possible confounding factors, such as time elapsed since most recent SRC, number of previous SRCs, psychological profile, diagnosis of attention-deficit/hyperactivity disorder, and any prescribed medications. Because the stratified prospective analysis of CLEI among players with HxSRC included only 14 cases, and the full-cohort prospective analysis of SRC occurrence included only 7 events, the precision of the estimated associations was not optimal. Despite these limitations, our findings strongly suggest that the combination of responses to the SFI and OWI surveys with metrics derived from the App FT can identify individual high school football players who are likely to derive benefit from interventions designed to reduce injury risk.

Previous research has demonstrated that both SRC and MSK injury incidence can be reduced through participation in a multimodal exercise program.[38] The effectiveness of a specific intervention might be enhanced by an individualized approach to injury risk reduction that targets resolution of risk factors identified by screening procedures. Our findings support the potential value of quantifiable survey responses and smartphone measurements of perceptual-motor performance to guide selection of interventions for injury risk reduction, but more research will be needed to confirm that such an individualized approach can reduce SRC and MSK injury incidence to a greater extent than a non-specific approach to injury prevention.

Conclusion

Evidence supports the potential for a multi-modal training program to reduce risk for both SRC and MSK injury, but there is no evidence the standard PPE process effectively identifies athletes who might derive greatest benefit from an injury risk reduction intervention. Our findings support the potential value of combining quantifiable survey responses with measures of perceptual-motor performance to classify an athlete's level of injury risk.

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