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# Post-Concussion Cognitive Declines and Symptomatology Are Not Related to Concussion Biomechanics in High School Football Players

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## Abstract

Concussion is a major public health concern with nearly 4 million injuries occurring each year in the United States. In the acute post-injury stage, concussed individuals demonstrate cognitive function and motor control declines as well as reporting increased symptoms. Researchers have hypothesized that the severity of these impairments is related to impact magnitude. Using the Head Impact Telemetry System (HITS) to record head impact biomechanics, we sought to correlate pre- and post-concussive impact characteristics with declines in cognitive performance and increases in concussion-related symptoms. Over four seasons, 19 high school football athletes wearing instrumented helmets sustained 20 diagnosed concussions. Each athlete completed a baseline computer-based symptom and cognitive assessment during the pre-season and a post-injury assessment within 24 h of injury. Correlational analyses identified no significant relationships between symptoms and cognitive performance change scores and impact biomechanics (i.e., time from session start until injury, time from the previous impact, peak linear acceleration, peak rotational acceleration, and HIT severity profile [HITsp]). Nor were there any significant relationships between change scores and the number of impacts, cumulative linear acceleration, cumulative rotational acceleration, or cumulative HITsp values associated with all impacts prior to or following the injury. This investigation is the first to examine the relationship between concussion impact characteristics, including cumulative impact profiles, and post-morbid outcomes in high school athletes. There appears to be no association between head impact biomechanics and post-concussive outcomes. As such, the use of biomechanical variables to predict injury severity does not appear feasible at this time.


**Key words:** acceleration; concussion; cognitive decline

## Introduction

Mild traumatic brain injuries, commonly referred to as concussions, occur nearly 4 million times each year in the United States as a result of participation in sport and recreational activities (Langlois et al., 2006). Numerous studies have defined the acute consequences of concussion in the days following injury. A recent meta-analysis quantified increases in self-reported symptoms and neuropsychological and balance test declines that are typical immediately following concussion (Broglio and Puetz, 2008). Injury recovery has also been thoroughly examined, as McCrea and associates (2003) reported that concussed young adults tended to return to their pre-injury performance levels by 7 days post-injury. Adolescent athletes have been purported to take nearly twice as long to recover (Field et al., 2003). However, a recent large-scale investigation of concussed high school athletes ($n = 544$) suggests that only 15% of these athletes experience symptoms lasting > 7 days, similar to their collegiate counterparts (Meehan et al., 2010). Although the understanding of the clinical course typically followed by athletes after concussion has improved, the initial identification of concussions by medical personnel remains the single largest obstacle in concussion management. For example, McCrea reported that > 53% of concussed high school athletes did not report their injury to an authority figure (McCrea et al., 2004). As such, there has been tremendous emphasis on developing technology that reduces the reliance on the athlete's subjective injury report.

The Head Impact Telemetry System (HITS) is a telemetered accelerometer system that can monitor the location and magnitude of head impacts sustained by football players in real time. In theory, such a system could be used to alert

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on-site medical personnel to athletes at risk for concussion based on biomechanical variables. Researchers have implemented the HITS in an attempt to identify a biomechanical threshold for injury. Indeed, studies have shown that combinations of biomechanical variables are better predictors of concussion than any single parameter. For example, Greenwald and associates (2008) used a weighted principal component analysis on 17 concussed collegiate and high school athletes and concluded that the best predictor of concussion was an algorithmic combination of linear acceleration, rotational acceleration, Head Injury Criterion (HIC), and impact location (referred to as the Head Impact Telemetry severity profile, or HITsp). Combined values > 63 resulted in 75% of the concussion being correctly predicted using biomechanical variables. Similarly, Broglio and associates (2010) used a classification and regression tree analysis on 13 concussed high school football players and found that injury was most likely to occur when rotational acceleration exceeded 5,582 rad/s$^2$, linear acceleration exceeded 96.1*g*, and the impact occurred in the front, side, or top of the helmet. To date, no threshold has been established that is sufficient for use as a sideline diagnostic tool. The HITS therefore remains useful for identifying individuals who have sustained high-magnitude impacts, which carry the greatest risk of injury.

The HITS' ability to quantify the mechanical properties of impacts may also permit it to be used as a predictor of injury severity and clinical outcomes. Ommaya and associates (1974) were the first to hypothesize that increasing impact magnitude would result in worsening cognitive outcomes. Although the hypothesis appears valid, the ability to capture *in vivo* data at the moment of injury has not been possible until recently. Surprisingly, a contemporary investigation using the HITS failed to demonstrate significant correlations between concussive impact magnitude and post-injury changes in symptoms, postural control, and cognitive function among collegiate athletes (Guskiewicz et al., 2007). No similar analyses have been published in high school athletes.

Despite ongoing advances in the understanding of impact biomechanics, concussive impacts at the high school level of play continue to be poorly characterized. As such, the purpose of this report is to evaluate the biomechanical properties of concussions occurring in high school football players, with specific emphasis on the relationships these parameters have to post-injury cognitive declines and symptomatology. More specifically, we aimed to evaluate the relationships between concussion symptoms and cognitive outcomes and the biomechanical properties both of the concussion-causing impact and the cumulative impact burden before and after the concussive impact.

## Methods

As part of an ongoing investigation of concussion biomechanics in high school football, 95 athletes from a single Class 3A team were enrolled between 2007 and 2010. Prior to data collection, all athletes were informed of the study's intent and signed an Institutional Review Board informed assent document. A separate parental consent was also obtained.

Upon enrollment, each athlete completed a pre-season ImPACT assessment (ImPACT Applications, Pittsburgh, PA, version 6.7). The computerized test battery takes 20–25 min to complete and includes sections on athlete demographics and concussion symptoms, as well as a cognitive evaluation. The symptom inventory, supported by the Concussion in Sport Group (Aubry et al., 2002), includes 22 symptoms scored for severity on a 0 to 6 Likert scale, with those ratings summed to generate a total symptom score. The cognitive evaluation includes six modules: word memory, design memory, X's and O's, symbol matching, color matching, and three letter memory. The program generates composite scores for verbal memory, visual memory, visual motor speed, and reaction time based on the athlete's test performance. An identical word group (word group 1) was used for all baseline examinations. ImPACT tests were administered in small groups (< 5) in a room free from noise and other distractions. A proctor was present at all times to provide directions and maintain the test environment quality. All baseline data were screened for internal validity. Those baseline tests indicative of low effort were repeated. ImPACT has previously been studied in athletes at the high school (Lovell et al., 2003), collegiate (Iverson et al., 2006), and professional (Pellman et al., 2006) levels. A detailed description of the ImPACT test modules and composite score calculations is available elsewhere (Lovell, 2007).

Each athlete was also issued a Riddell (Elyria, OH) Revolution helmet by the team, which the investigators equipped with a HITS (Simbex LLC; Lebanon, NH) encoder. The HITS encoder is composed of six single axis accelerometers, a data storage unit, a wireless telemetry unit, and a battery. When in range of a sideline computer, all data are downloaded and stored in real time. When out of range, or when the computer is unavailable, up to 100 impacts are stored locally. The encoder was retrofitted between the existing helmet padding such that helmets continued to meet National Operating Committee on Standards for Athletic Equipment (NOCSAE) standards for safety once the HITS encoder was in place. The HITS had been validated against a 3-2-2-2 Hybrid III dummy for the detection of both impact location and magnitude (Crisco et al., 2004). The system had been used in a number of concussion biomechanics investigations at both the collegiate (Brolinson et al., 2006; Crisco et al., 2010; Duma et al., 2005; Greenwald et al., 2008; Manoogian et al., 2006) and high school (Broglio et al., 2009, 2010; Schnebel et al., 2007) levels.

For data to be recorded by the HITS, the acceleration of a single accelerometer must exceed a 15*g* threshold. Following impact, a total of 40 ms of data are recorded, including 8 ms prior to the impact and 32 ms following. The software automatically calculates peak linear acceleration, peak rotational acceleration (derived from the x-axis and y-axis angular accelerations), impact location, and HITsp associated with each impact, and provides a date and time stamp for later download and analysis. Data were recorded during all sessions (i.e., games and practices) and were screened on a daily basis to ensure errant impacts (e.g., dropped helmet) were excluded from the database. A more detailed description of the HITS technology and data recording and management has been reported elsewhere (Greenwald et al., 2008).

For the purpose of this investigation, concussion was defined by the American Academy of Neurology Practice parameter, which states ''Concussion is a trauma-induced alteration in mental status that may or may not involve loss of consciousness (American Academy of Neurology, 1997).'' The investigative protocol was to not use the HITS to diagnose an individual with a concussion, but rather to identify athletes who had sustained a large magnitude impact. As such, impacts occurring during games and practices suspected of resulting in a concussion were identified by an investigator (S.P.B.), but injury diagnosis was made by the team's certified athletic trainer or physician. No athlete was removed from play because he had sustained a large magnitude impact. Rather, such athletes were evaluated when they came to the sideline between series or during a timeout. In some instances, athletes may have sustained a significant impact, denied symptoms upon initial evaluation, returned to play, and later reported concussion-related symptoms. In these instances, the data were reviewed with the athlete's assistance to identify the most significant impact at the approximate time of injury. Injuries were not graded, because of the general lack of support for the use of grading scales (McCrory et al., 2009) and a lack of evidence supporting the use of grading scales to accurately reflect injury severity (Lovell et al., 2004). Time until the athlete was cleared to begin a return to play protocol, however, was used as an indicator of injury severity. Every concussed athlete completed a post-injury ImPACT evaluation within 12–18 h of injury diagnosis. The after-injury ImPACT testing protocol was identical to that used during baseline testing, except that the second word group was used.

### *Data analysis*

Descriptive statistics were calculated for athlete demographics, impact characteristics, post-concussion symptoms, and cognitive outcomes. Impact characteristics relative to the injurious impact included time from session start until injury, time from the previous impact, linear acceleration, rotational acceleration, and HITsp. We also calculated the number of impacts, cumulative linear acceleration, cumulative rotational acceleration, and cumulative HITsp values associated with all impacts prior to and following the injury. After-injury symptom and cognitive outcomes were represented as the difference in reported symptoms from baseline and the percent change in ImPACT verbal memory, visual memory, visual motor speed, reaction time, and impulse control scores from baseline.

To estimate the predictive value of each of the above-mentioned biomechanical variables, we performed Pearson correlations on the impact characteristics and the associated symptom and cognitive outcomes. Stepwise linear regression analyses were planned, should multiple significant bivariate correlations be revealed. Statistical significance was defined as $p < 0.05$.

## Results

Ninety-five athletes were enrolled across the 4-year investigation. Participant demographics [mean (standard deviation)] at enrollment were: 16.7 (0.8) years, 180.2 (6.7) cm, and 85.6 (18.3) kg. Twenty-three athletes reported at least one previously diagnosed concussion (mean $0.3 \pm 0.7$, range 1–6). Overall, athletes participated in 190 practices and 50 games that collectively resulted in 102,218 head impacts. A total of 244 impacts were identified as errant and therefore removed from the data set, leaving 101,994 valid impacts. Of these, 20 impacts resulted in concussions in 19 athletes. Table 1 presents the demographic information for the injured athletes.

When only the 20 concussive impacts were evaluated, the mean time from the previous impact was 8:26 (10:40) with a resulting linear acceleration of 93.6 (27.5) $g$, rotational acceleration of 6402.6 (1753.9) rad/s$^2$, and HITsp value of 63.4 (20.0). Concussive impacts occurred primarily to the front of the helmet ($n=11$), but also to the top ($n=3$), back ($n=1$), and side ($n=5$). On the day of injury, the athletes sustained a mean of 25.0 (18.3) impacts prior to concussion and a cumulative impact burden of 755.9 (560.1) $g$, 47735.0 (34551.5) rad/s$^2$, and 428.5 (282.8) HITsp. Following the concussive blow, athletes sustained an additional 13.1 (17.7) impacts resulting in a cumulative linear acceleration of 406.6 (581.3) $g$, a cumulative rotational acceleration of 23978.3 (3,2230.8) rad/s$^2$, and a cumulative HITsp value of 226.1 (281.0). Individual athlete data are presented in Tables 1 and 2.

The concussed athletes demonstrated overall mean (standard deviation) declines in verbal memory (-7.3 [13.3] %), visual memory (-10.4 [14.2] %), visual motor speed (-12.9 [27.5] %), reaction time (9.5 [12.9] %), and impulse control (72.1 [159.2] %) on their after injury ImPACT tests. Symptom scores increased by 14.6 (13.9) points following injury. Athletes were cleared to begin a return to play exertion protocol 5.2 (3.5) days following injury. Table 3 reports after-injury symptom score and cognitive performance changes for each concussed athlete.

Pearson correlation analysis revealed only one statistically significant relationship (at $\alpha=0.05$) between the HITsp value of the injurious impact and post-injury change in ImPACT impulse control composite score ($r=-0.50$, $p=0.04$). However, we feel that this finding most likely represents type I error, as a result of conducting nearly 100 correlational analyses. When a Bonferroni correction is applied to adjust the significance threshold for multiple comparisons, this finding is rendered non-significant. No other significant relationships between impact characteristics (e.g., peak linear and rotational accelerations, HITsp) or athlete demographics (e.g., previous number of concussions) and symptom or ImPACT change scores or number of days until recovery were identified ($p$'s$>0.05$). Similarly, there were no significant relationships identified between pre- or post-impact cumulative biomechanical variables (e.g., cumulative linear acceleration [$g$] prior to or following concussion) and symptom or ImPACT change scores or number of days until recovery ($p$'s$>0.05$).

As the single significant bivariate correlation was thought to be spurious, regression models were not used to further explain the relationship between concussion biomechanics and post-injury cognitive and symptom outcomes.

## Discussion

This investigation is part of an ongoing study evaluating the biomechanical properties of concussion in high school football. Our most significant finding is the non-significant relationship between biomechanical impact variables and injury severity measures. These negative findings mirror previous work on collegiate athletes (Guskiewicz et al., 2007), however we assessed a number of additional impact variables that were not included in the collegiate-level study. More specifically, our analysis included not only biomechanical properties of the concussive impact itself, but also a number of impact variables reflecting the cumulative impact burden both before and after the concussive impact.

Our data allow some comparisons to be drawn between this study involving high school athletes and the previous collegiate

Table 1. Characteristics of Each Athlete and the Impact Resulting in Concussion
Player and Impact Characteristics

| *Subject ID* | *Session type* | *Age (years)* | *Mass (kg)* | *Height (cm)* | *Previous concussions* | *Position* | *Impact location* | *Resultant linear acceleration (g)* | *Resultant rotational acceleration (rad/s$^2$)* | *HITsp* | *Time (min:sec) from start of session* | *Time from previous impact (min:sec)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *2* | Game | 17.5 | 68.2 | 175.3 | 1 | Quarterback | Top | 102.6 | 5582.6 | 73.4 | 153:39 | 6:37 |
| *7* | Game | 16.7 | 93.2 | 190.5 | 1 | Offensive Line | Top | 146.0[b] | 5929.4 | 61.9[b] | 122:00 | 5:42 |
| *8* | Game | 17.7 | 80.5 | 167.6 | 0 | Full Back | Left | 74.6 | 5581.9 | 48.2 | 76:31 | 0:26 |
| *10* | Game | 15.6 | 84.1 | 190.5 | 1 | Full Back | Front | 122.0 | 7103.1 | 94.1 | 31:25 | 31:25 |
| *27* | Game | 19.0 | 90.0 | 190.5 | 0 | Quarterback | Front | 130.6[b] | 7992.9 | 98.1[b] | 107:06 | 0:42 |
| *32* | Game | 16.2 | 100.0 | 182.9 | 2 | Defensive Line | Front | 111.3 | 9515.5[b] | 83.3[b] | 103:29 | 0:46 |
| *32* | Game | 16.9 | 100.0 | 182.9 | 3 | Defensive Line | Left | 107.6 | 6634.3 | 74.0[b] | 16:51 | 7:08 |
| *35* | Game | 16.2 | 86.4 | 175.3 | 0 | Running Back | Front | 116.2 | 6640.7 | 73.0 | 125:00 | 14:02 |
| *36* | Game | 16.4 | 70.5 | 180.3 | 0 | Cornerback | Front | 97.6 | 8529.7[b] | 70.0[b] | 87:52 | 19:02 |
| *37* | Game | 17.0 | 78.2 | 180.3 | 5 | Wide Receiver | Front | 66.3 | 5933.0 | 60.5 | 87:12 | 39:04 |
| *38†* | Game | 17.9 | 79.1 | 188.0 | 0 | Wide Receiver | Top | 114.4[b] | 3317.5 | 63.6[b] | 113:37 | 7:03 |
| *42* | Game | 15.8 | 72.3 | 180.3 | 1 | Strong Safety | Left | 74.0 | 6516.2 | 52.0 | 22:51 | 3:47 |
| *45* | Practice | 16.5 | 83.2 | 175.3 | 0 | Offensive Line | Front | 99.1[b] | 7997.2 | 80.0[b] | 5:44 | 4:46 |
| *47* | Practice | 16.5 | 111.4 | 170.2 | 0 | Defensive Line | Front | 100.9 | 7967.1 | 73.0 | 9:21 | 0:54 |
| *61* | Practice | 17.0 | 78.2 | 180.3 | 2 | Tight End | Front | 85.3 | 4870.2 | 65.0 | 69:18 | 1:22 |
| *69* | Practice | 17.0 | 79.5 | 180.3 | 2 | Linebacker | Right | 52.7 | 4664.6 | 34.6 | 91:20 | 2:12 |
| *71*[a] | Game | 16.8 | 79.6 | 175.3 | 1 | Strong Safety | Front | 48.0 | 4280.4 | 27.9 | 49:58 | 1:35 |
| *73* | Game | 17.0 | 78.2 | 180.3 | 1 | Linebacker | Left | 66.5 | 4655.3 | 40.5 | 117:07 | 15:54 |
| *74*[a] | Game | 16.8 | 85.5 | 182.9 | 1 | Quarterback | Back | 52.9 | 4858.1 | 27.4 | 116:30 | 0:43 |
| *80* | Game | 15.5 | 83.6 | 177.8 | 0 | Running Back | Front | 102.7 | 9481.5 | 68.1 | 100:22 | 5:28 |

[a]Athlete sustained a brief (~10sec) loss of consciousness at time of injury.
[b]Indicates that this aspect of the impact was the largest sustained by the athlete during the competitive season.

level study that examined the relationship between concussion biomechanics and clinical outcomes. Guskiewicz and associates (2007) reported mean peak linear and rotational accelerations associated with concussive impacts of 102.8*g* and 5331.6 rad/s$^2$, respectively. The mean peak linear acceleration associated with injury in this study was slightly lower (93.6), whereas the corresponding rotational acceleration value was slightly higher (6402.6 rad/s$^2$). After-injury symptom score changes were virtually identical between the studies, with a mean increase of 14.6 points in our high school group as compared to 13.5 in the collegiate group. Protocol differences between the two studies precluded direct comparison of changes in cognitive test performance, postural control, and recovery time.

The lack of correlation between impact magnitude and cognitive decline is, perhaps, surprising given the long-standing belief that magnitude of head acceleration/deceleration associated with impact is related to the degree of post-injury impairment (Ommaya et al., 1974). This theory is partly supported through finite element analysis of head impacts sustained by professional football players that examined the relationship between head kinematics and the estimated resultant intracranial pressure response. The authors reported that greater linear and rotational accelerations increased intracranial pressure and that sudden impact-associated changes in intracranial pressure had a large influence on the likelihood of concussion. How these variables may influence the clinical presentation of symptoms and cognitive performance was not known or reported (Zhang et al., 2004). Our data however, as well as the collegiate-level data presented elsewhere do not support the theory that greater impact kinetics result in greater neurological impairment. The reason for this apparent lack of *in vivo* association is unclear.

In part, one explanation may stem from the very nature of concussion being a functional, more so than a structural, injury. In this sense, the neurological signs and symptoms associated with concussion are the result of a breakdown in communication across complex neural networks, as opposed to being the result of one area of the brain being injured, as is seen in more focal processes such as stroke or tumor. It is not surprising therefore, that measuring the clinical effects of head impacts by specific location does not produce a consistent pattern, or result in significant findings in this study. It is also important to consider the tremendous variability that exists in brain physiology from one individual to the next, and how dynamic brain physiology is over time. For these reasons, the potential for any particular impact to result in a concussion probably depends upon many intrinsic factors, which may vary more between individuals than do the type and magnitude of forces experienced by the brain, and may further explain the lack of relationship between biomechanical factors and clinical outcomes.

For example, cellular level individual differences in structure and function, cranial and vascular morphology, or other unmeasured factors may influence the variable response to impact. Bayly and associates (2005) implemented a finite element analysis model to quantify brain deformation associated with a 2-cm drop resulting in a posterior cranial impact. In this model, the vasculature, nerves, and dura acted in conjunction to tether the brain, resulting in rotation of the brain's center of gravity around a point near the sella and suprasellar space. This ultimately caused anterior compression and posterior stretching to result from the initial posterior impact. The brainstem showed shortening and shearing caused by the downward and forward rotation of the posterior inferior brain tissue. The authors concluded that the anterior region of the brain impacted the skull before the occipital region struck the back of the skull, because of basal tethering. Importantly, the static structures that were

Table 2. Impact Characteristics Prior to and Following Concussion. Pre- and Post-Impact Characteristics

| *Subject ID* | *No. impacts prior to concussion* | *Cumulative linear acceleration (g) prior to injury* | *Cumulative rotational acceleration (rad/s/s) prior to injury* | *Cumulative HITsp prior to injury* | *No. impacts following concussion* | *Cumulative linear acceleration (g) following concussion* | *Cumulative rotational acceleration (rad/s/s) following concussion* | *Cumulative HITsp following concussion* |
|---|---|---|---|---|---|---|---|---|
| *2* | 23 | 557.2 | 33920.2 | 374.5 | 1 | 12.8 | 527.3 | 12.9 |
| *7* | 18 | 439.4 | 19666.4 | 278.8 | 1 | 25.8 | 510.5 | 191.2 |
| *8* | 26 | 863.5 | 61730.0 | 441.3 | 27 | 806.6 | 51658.6 | 413.4 |
| *10* | 2 | 131.0 | 7280.5 | 105.5 | 15 | 394.5 | 25283.2 | 239.7 |
| *27* | 54 | 1436.1 | 86776.5 | 757.5 | 7 | 187.4 | 8921.3 | 84.8 |
| *32* | 26 | 992.3 | 58980.6 | 507.6 | 43 | 1501.1 | 80502.2 | 766.6 |
| *32* | 13 | 489.2 | 20547.0 | 205.4 | 70 | 2177.5 | 120658.5 | 1070.4 |
| *35* | 71 | 2269.0 | 133492.4 | 1139.4 | 28 | 1104.3 | 57422.9 | 503.6 |
| *36* | 10 | 231.3 | 14384.7 | 160.6 | 11 | 215.4 | 13189.6 | 139.7 |
| *37* | 19 | 439.4 | 35852.8 | 291.2 | 17 | 523.1 | 40538.1 | 332.4 |
| *38* | 29 | 808.8 | 50116.5 | 478.7 | 1 | 27.3 | 641.6 | 63.6 |
| *42* | 9 | 319.8 | 21402.1 | 207.1 | 2 | 48.0 | 3789.3 | 26.0 |
| *45* | 3 | 184.2 | 14342.2 | 133.0 | 11 | 320.2 | 24576.5 | 212.9 |
| *47* | 6 | 321.6 | 20544.4 | 181.0 | 10 | 233.6 | 10592.7 | 121.6 |
| *61* | 13 | 376.9 | 27292.2 | 270.4 | 4 | 105.0 | 8462.4 | 73.1 |
| *69* | 18 | 396.9 | 31178.0 | 249.8 | 0 | 0.0 | 0.0 | 0.0 |
| *71* | 45 | 1309.4 | 95158.2 | 812.7 | 0 | 0.0 | 0.0 | 0.0 |
| *73* | 29 | 720.9 | 46294.8 | 463.7 | 1 | 27.5 | 2522.9 | 19.0 |
| *74* | 37 | 1368.5 | 79057.1 | 687.7 | 0 | 0.0 | 0.0 | 0.0 |
| *80* | 48 | 1463.4 | 96683.1 | 823.6 | 12 | 422.3 | 29768.0 | 250.1 |

Table 3. Concussion Duration and After-Injury Changes in Symptom Scores and ImPACT Test Performance. Concussion Outcome Measures

| *Subject ID* | *Days until cleared to begin RTP protocol* | *Change in symptom score* | *Change in verbal memory (%)* | *Change in visual memory (%)* | *Change in visual motor speed (%)* | *Change in reaction time (%)* | *Change in impulse control (%)* |
|---|---|---|---|---|---|---|---|
| *2* | 1 | 0 | 1.0% | −9.0% | 23.0% | 4.0% | −33.0% |
| *7* | 10 | **19** | **−14.0%** | **−24.0%** | **−17.0%** | −2.0% | 71.0% |
| *8* | 12 | **36** | **−26.0%** | −19.0% | 5.0% | **23.0%** | −20.0% |
| *10* | 8 | 4 | −11.0% | **−10.0%** | 19.0% | **8.0%** | −25.0% |
| *27* | 3 | 0 | 8.0% | **−25.0%** | **−24.0%** | **26.0%** | 56.0% |
| *32* | 4 | **43** | **−20.0%** | **−20.0%** | **−65.0%** | **23.0%** | −22.0% |
| *32* | 8 | 3 | 6.0% | 4.0% | **−56.0%** | 8.0% | −36.0% |
| *35* | 3 | 3 | −5.0% | 9.0% | **−13.0%** | **16.0%** | 50.0% |
| *36* | 1 | **16** | **−18.0%** | −9.0% | **−33.0%** | 1.0% | 82.0% |
| *37* | 4 | 0 | **−12.0%** | −3.0% | 18.0% | 5.0% | −33.0% |
| *38* | n/a[a] | | | | | | |
| *42* | 2 | 6 | 3.0% | **−22.0%** | 15.0% | −9.0% | 183.0% |
| *45* | 1 | 6 | 26.0% | 7.0% | 22.0% | −5.0% | −33.0% |
| *47* | 4 | **14** | **−19.0%** | −12.0% | −12.0% | **26.0%** | 150.0% |
| *61* | 12 | **41** | **−18.0%** | **−23.0%** | 8.0% | 0.0% | −59.0% |
| *69* | 2 | 9 | 2.0% | **−25.0%** | −10.0% | **30.0%** | 67.0% |
| *71* | 5 | **29** | **−16.0%** | 17.0% | **−31.0%** | **23.0%** | 638.0% |
| *73* | 5 | **16** | −9.0% | **−35.0%** | **−18.0%** | −10.0% | 217.0% |
| *74* | 5 | **22** | 5.0% | 1.0% | **−59.0%** | **15.0%** | 0.0% |
| *80* | 8 | **10** | **−21.0%** | 0.0% | **−18.0%** | −2.0% | 117.0% |

Positive change in symptom scores represent greater reported symptom severity. Declines in ImPACT test performance are represented by negative verbal memory, visual memory, and visual motor speed change scores and positive reaction time and impulse control change scores. ImPACT scores in **bold** represent a clinically meaningful change.

[a]No follow-up testing was completed, as the athlete was disqualified from football for an orthopedic injury.

determined to be responsible for restricting brain motion vary between individuals and may contribute to the variability in after-injury outcomes among athletes. Indeed, Table 1 demonstrates a wide range of impact characteristics among athletes relative to their concussive events.

Another factor that may have contributed to our inability to identify associations between impact biomechanics and concussion outcomes are weaknesses inherent to the cognitive assessment tool we used in this study. The reliability of ImPACT is known to vary based on the length of time between baseline and post-injury evaluations. Test–retest intervals of 2 weeks have been shown to have the best reliabilities, with intra-class correlation coefficients ranging from 0.54 to 0.76 (Iverson et al., 2003). However, reliability drops to 0.15 to 0.39 at longer, more clinically relevant time intervals (Broglio et al., 2007a). A potential result of this reduced stability at the time intervals associated with this study is a lack of sensitivity to concussion's deleterious cognitive effects. That is, the sensitivity of ImPACT to cognitive decline is estimated to be 62% when using just the cognitive test modules (Broglio et al., 2007b) and 79–82% when both the cognitive and symptom measures are included (Broglio et al., 2007b; Schatz et al., 2006). As such, ImPACT's sensitivity in measuring cognitive change after head impact should be carefully considered. Indeed, the ability of any particular cognitive tool to fully characterize post-morbid cognitive changes is limited by the nature of the tests being used. That is, these tests are not diagnosing athletes with concussions, but rather measuring a change in cognitive performance. These are probably limiting factors in correlating impact biomechanics with post-injury changes, and future works should also include measures of motor control.

### *Limitations*

This study attempted to explore the relationship between impact biomechanics and concussion outcomes, but there are many difficulties inherent to this type of research. For example, every head impact has associated linear and rotational accelerations, directionality, and duration. The HITsp combines elements of each of these, but a single biomechanical variable that accurately describes concussive impacts remains elusive. An additional challenge relates to quantifying the cumulative impact burdens sustained by these athletes prior to and following concussion. Despite high school athletes sustaining nearly 700 impacts to the head each season (Broglio et al., 2011), the cumulative sum of linear acceleration, rotational acceleration, and HITsp values has not been demonstrated to be predictive of brain disease risk. However, in the absence of a validated measure of cumulative impact burden, we feel that exploration of these values is warranted. Furthermore, every concussion is a unique injury in a unique individual and presently no single outcome measure can fully capture the extent or character of the injury. Although we included multiple outcome measures in this study, the complexity of the human brain as well as the complex pathophysiology of concussion make it an extremely difficult injury to quantify. Also, because of resource limitations, some outcome measures that are known to be sensitive to the effects of concussion, such as standardized balance or motor tests, were not used in this study. Lastly, many of the injured athletes reported on here continued to play after their presumed concussive impact, only later reporting their symptoms. This is reflective of the inherent difficulty in diagnosing concussions. Despite several attempts to use biomechanical variables as a diagnostic tool, an accurate combination remains elusive (Broglio et al., 2010; Eckner et al., 2011; Greenwald et al., 2008). As a result, the impact responsible for causing concussion in these athletes cannot be identified with absolute certainty. As such, interpretation of the results should be handled cautiously.

## Conclusions

This investigation is the first to evaluate the association between head impact biomechanics and clinical outcomes following concussion in high school athletes. It is also the first to investigate the relationship between the cumulative burden of head impacts sustained by an athlete over the course of an entire practice or game, and post-concussive outcomes. The overall lack of a relationship between these measures mimics similar findings reported at the collegiate level. There is no evidence to support the notion that the biomechanics of a concussive head impact, or of the head impacts leading up to or following the concussive impact, are predictive of injury severity or time lost. As such, clinicians charged with the management of sport concussions should continue to be vigilant following head impacts across a wide spectrum of impact magnitudes and impact histories. Each concussed athlete should be evaluated on a case-by-case basis with implementation of a broad array of assessment tools including symptom, cognitive, and motor control measures. The significance of impact biomechanics with respect to concussion risk and clinical severity need to be more clearly defined before biomechanical measures can play a useful role in the routine detection and management of concussed athletes. For now, their application remains limited to that of a research tool.

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## Author Disclosure Statement

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