MEASUREMENT OF HEAD IMPACTS IN COLLEGIATE FOOTBALL PLAYERS: CLINICAL MEASURES OF CONCUSSION AFTER HIGH- AND LOW-MAGNITUDE IMPACTS

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OBJECTIVE: It has been speculated that a theoretical injury threshold of 70 to 75 g may exist for concussions in football players. We aimed to investigate acute balance and neurocognitive performance after head impacts exceeding a theoretical injury threshold in the absence of both self-reported symptoms and a concussion diagnosis 24 hours before testing.

METHODS: Forty-three Division I collegiate football players participated in this double-blind, repeated-measures study. Subjects participated in three test sessions (baseline, low impact, and high impact) separated by at least 2 weeks. The Head Impact Telemetry System (Simbex, Lebanon, NH) recorded real-time head impacts sustained during practices and games. The Automated Neuropsychological Assessment Metrics assessed neurocognitive performance. The NeuroCom Sensory Organization Test (NeuroCom International Inc., Clackamas, OR) assessed postural stability. The Graded Symptom Checklist evaluated symptom presence and severity in our participants.

RESULTS: After the low-impact test session (< 60 g), we observed improvements in the Math Processing ($F_{1, 26} = 9.797$; $P = 0.004$), Matching to Sample ($F_{1, 26} = 6.504$; $P = 0.017$), and Sternberg Procedure ($F_{1, 26} = 5.323$; $P = 0.030$) Automated Neuropsychological Assessment Metrics test modules. Statistically significant differences were also observed after the high-impact test session (> 90g) with improvements in Math Processing ($F_{1, 22} = 16.629$; $P < 0.001$), Procedural Reaction Time ($F_{1, 22} = 14.668$; $P < 0.001$), and the total number of symptoms reported ($F_{1, 22} = 10.267$; $P = 0.004$). Neurocognitive improvements were likely attributed to a learning effect.

CONCLUSION: Our findings suggest that sustaining an impact greater than 90 g does not result in acute observable balance and neurocognitive deficits within 24 hours of sustaining the impact. Although previous studies have suggested a theoretical injury threshold, none have been founded on empirical data collected on the playing field in real-time. Future studies should consider the cumulative effects of impacts of varying magnitudes.

KEY WORDS: Biomechanics, Helmet, Injury threshold, Mild traumatic brain injury, Subconcussive injury

Concussions are of growing concern throughout competitive sports. A concussion is defined as a traumatically induced alteration in neural function that may or may not involve loss of consciousness (3). Despite significant research being conducted in the area of sports-related concussion, much is still unknown about the injury. An estimated 300,000 sports-related concussions are reported each year in the United States among children, adolescents, and young adults (1). Published research has promoted improvements in equipment, and changes in rules have been introduced in an attempt to reduce the incidence of concussion among a continually growing athletic population (23). Despite the improvements to facial and head protection, and increased emphasis on proper tackling

techniques, the number of athletes who sustain concussions remains high at the college level (20).

There is no research-based format for managing concussion. More than 22 grading scales and return-to-play guidelines have been presented in the literature, but none of these have been empirically supported. American football, often categorized as a high-risk collision sport, is one of the most commonly studied sports in the sports-related concussion research model because players have a relatively high incidence of concussion. Players repeatedly sustain impacts to the head that are comparable to those sustained in car crashes (28). Many concussions are underreported and younger athletes are less likely to report their symptoms to the medical professional entrusted with his or her immediate care (4). This is attributable to a number of factors that vary with both the sport and athlete. Preventing morbidity from concussion has always been a goal of the medical field; therefore, a need for exploring new methods of better monitoring the impacts an athlete may sustain during participation remains an area of much interest in the sports medicine community. Thus, there is still much to be learned regarding exactly how the impacts that a football athlete sustains to the head on a daily basis affect the brain. Although laboratory testing of head impact biomechanics has become quite advanced, athletic environments offer a rich opportunity for collecting data on large numbers of head impacts sustained by many players. Without this knowledge, clinicians must often resort to the self-report of symptoms by their patients who are athletes.

Although a number of symptoms typically follow a concussion, these might not present immediately; they can manifest 24 hours after the initial impact. By further examining the location, duration, and magnitude of impacts that football players are sustaining on a daily basis, it has been suggested that medical personnel will be able to provide better medical care to the athlete in terms of the immediate recognition of injury and the effects it may have on the body. Much is still unknown about the clinical manifestations observed in athletes after measurable impacts greater than previously reported injury thresholds.

The primary purpose of this study was to compare measures of balance performance and neurocognitive function at baseline with those obtained after the participant had sustained an impact to the head with a magnitude of linear acceleration greater than 90 g. The secondary purpose of this study was to compare the measures of balance and neurocognitive function at baseline with those obtained after the participant had sustained an impact to the head with a magnitude of linear acceleration less than 60 g. The overall objective was to observe whether or not magnitude of head impacts affected the participants' balance and neurocognitive performance in the absence of both self-reported symptoms and a concussion diagnosis 24 hours before testing.

PATIENTS AND METHODS

Forty-three Division I male collegiate football players (age, 20.74 ± 1.62 yr; mass, 110.29 ± 15.78 kg; height, 186.46 ± 6.35 cm) were initially enrolled in this study and completed preseason baseline testing. Subsequently, 22 players were used in the comparison of scores between impacts greater than 90 g (high) and preseason baseline, whereas 26 completed testing in the less than 60 g (low) and baseline comparison. Fourteen players completed testing under both conditions. Our sample included defensive linemen, offensive linemen, wide receivers, linebackers, offensive backs, and defensive backs. Subjects had no medical conditions or injury to the lower extremity within 6 weeks of testing that may have affected their ability to perform balance tasks. Exclusion criteria included previously diagnosed head injury within the past 6 months or having a current vestibular, visual, or balance disorder. Participants underwent preseason baseline testing before the start of the season. The participants were given a packet with information about the study and what it entailed. All subjects signed the appropriate informed consent form that was approved by the university's biomedical Institutional Review Board.

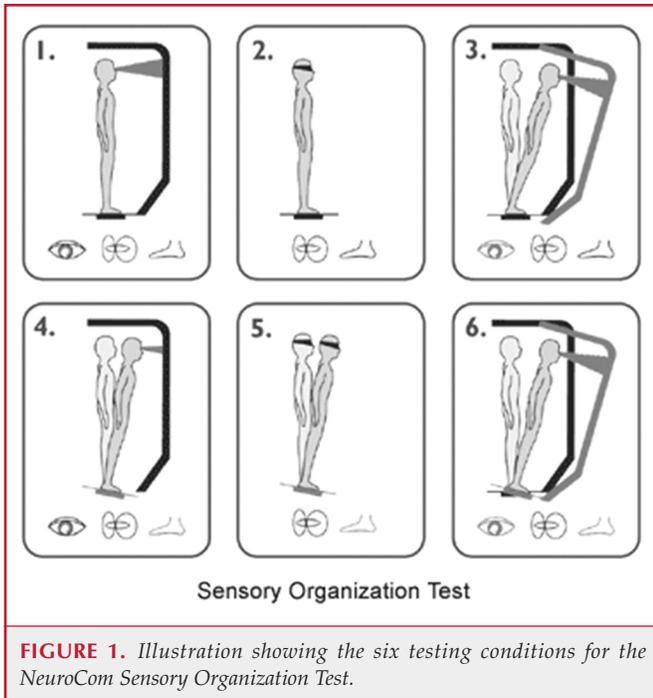### Instrumentation

Head Impact Telemetry System

To isolate players who had sustained a given qualifying impact magnitude, we used the Head Impact Telemetry (HIT) System (Simbex, Lebanon, NH). The HIT System obtained data from accelerometer units comprised of six spring-mounted single-axis accelerometers embedded in Riddell VSR-4 or Revolution football helmets (Riddell Corp., Elyria, OH). The signal transducer was linked to a laptop computer in the Sideline Response System through radiowave transmission (903–927 MHz). The information was stored on an onboard memory system (up to 100 impacts) or was immediately transferred to the laptop computer system (eight-bit, 1000 Hz/channel). The HIT System has the ability to simultaneously monitor a total of 64 players. The downloaded impacts were then processed through a validation algorithm and peak head linear acceleration was computed. The HIT System was previously validated in laboratory testing with Hybrid dummies equipped with football helmets (5, 6, 19, 24).

Sensory Organization Test

The Sensory Organization Test (SOT) (NeuroCom International Inc., Clackamas, OR) was used to assess participants' balance performance during preseason baseline screening and in both follow-up test sessions. The SOT is able to assess balance performance by disrupting input from the visual, vestibular, and somatosensory systems. The participants stood with feet shoulder width apart on the force platform and arms comfortably at both sides. Participants were directed to complete three 20-second trials of six different sensory conditions in random order. The six testing conditions were as follows: normal vision and normal support surface, eyes closed with normal support surface, sway-referenced visual input with normal support surface, normal vision with sway-referenced support surface, eyes closed with sway-referenced support surface, and normal vision with sway-referenced visual and support surface (*Fig. 1*). The outcome measures represented how much that particular component (visual, vestibular, somatosensory) contributed to the overall composite score. The SOT has previously been used to document balance performance deficits in concussed athletes lasting as long as 4 to 7 days (14).

Automated Neuropsychological Assessment Metrics

Participants were tested using the Automated Neuropsychological Assessment Metrics (ANAM) battery to assess neurocognitive function. This computerized test battery consists of seven separate test modules that include the following: Simple Reaction Time 1, Math

FIGURE 1. *Illustration showing the six testing conditions for the NeuroCom Sensory Organization Test.*

Processing, Matching to Sample, Procedural Reaction Time, Code Substitution, Sternberg Procedure, and Simple Reaction Time 2. Although the order by which the modules are presented to the participant remained constant, the stimuli in each of the modules were randomly presented in follow-up test sessions to limit practice effects. Other modules exist within the ANAM test software that were not included in the sports medicine battery. The sports medicine battery has been used at our institution for more than 5 years and has been designed to maximize the benefits of computerized testing while minimizing the time needed to complete preseason baseline and postinjury follow-up testing. The concurrent validity with traditional neuropsy-

chological measures, including the Hopkins Verbal Learning Test, the Controlled Oral Word Association Test, Digit Symbol, Symbol Search, and the Brief Test of Attention, has been previously established (27). Test-retest reliability has also been evaluated and has been reported in a recent publication (2). These test modules and the cognitive domains they assess are presented in *Table 1*.

Graded Symptom Checklist

The Graded Symptom Checklist (GSC) is a self-report symptom scale that assesses the presence of 18 concussion-related symptoms and their respective severity using a seven-point Likert scale ranging from asymptomatic (0) to mild (1) to severe (6). During the preseason baseline evaluation, participants were instructed to rate the presence and severity of any symptom they reported feeling at least three times per week over the course of the summer before the baseline test session. During follow-up test sessions, the participants were asked to rate the presence and severity of their symptoms based on what they felt at the time of testing. The GSC has been published previously (25).

Procedures

This was a double-blind, repeated-measures study. The primary investigator (MAM) was blinded from the test condition and the test results until the completion of the study. The participants were also blinded as to which test condition was being assessed. The primary investigator performed the testing for all preseason baseline screening and follow-up test sessions. One of the coinvestigators (JPM) identified players to be tested after a given practice or game but blinded the primary investigator from which condition they were being tested. Once the season was complete, clinicians trained in the evaluation of the tests interpreted the results. Random test administration order occurred during this study to remove possible effects of testing order. The procedures used for the preseason baseline evaluation and those used for follow-up test sessions are detailed subsequently.

Preseason Baseline Evaluation

Subjects were seated in a quiet room to perform the computerized neurocognitive testing using the ANAM battery. This testing procedure, consisting of seven modules, took approximately 20 minutes to

Test module	Cognitive domain(s)	Description of test module
Simple Reaction Time 1	Reaction time	User quickly clicks mouse when stimulus "*" appears on screen
Math Processing	Mental processing speed and mental efficiency	Basic arithmetic operation is presented on the screen; athlete left-clicks mouse if solution is <5 and right-clicks if solution >5
Matching to Sample	Visual memory	A 4 × 4 checkerboard matrix is presented for 2 sec and then disappears; two side-by-side matrices appear after an interval; athlete indicates which matrix (left or right) exactly matches the original matrix
Procedural Reaction Time	Reaction time and working memory	Athlete clicks left mouse button if "2" or "3" appear on the screen; right mouse button is clicked if "4" or "5" appear on the screen
Code Substitution	Delayed memory	Nine symbols and digits appear on top of screen; symbol–digit pairings appear on bottom; athlete responds to correct pairings
Sternberg Procedure	Working memory	Participants memorize a string of six letters; individual letters then appear on screen; athletes must decide whether the letter belongs to the original list of letters
Simple Reaction Time 2	Reaction time	Similar to Simple Reaction Time 1, conducted at end of battery

TABLE 1. The Automated Neuropsychological Assessment Metrics test modules and cognitive domains assessed

complete. Balance performance was measured using the SOT. Directions were verbally recited to the athlete by the examiner before the start of test administration. The participant was directed to stand as motionless as possible in normal stance for each trial with feet shoulder width apart. Testing lasted approximately 10 minutes. A GSC was also completed by each athlete on which he reported and rated any symptom he experienced regularly three or more times per week in the 3 months before the time of test administration.

Postimpact Evaluation

Postimpact evaluations took place at least 2 weeks after the start of preseason camp and continued until the completion of the fall season. Evaluations resumed in the ensuing spring season to assess the desired number of subjects. As stated earlier, athletes were identified by the coinvestigator (JPM) based on the impacts they sustained during a given practice or game. The coinvestigator targeted athletes who met one of the following criteria: they had sustained at least one impact greater than 90 g or they had sustained no impacts greater than 60 g. Testing session order was randomized among the population. Testing procedures performed during the preseason baseline screening were repeated within 24 hours after the end of a given practice or game in which the participant met the aforementioned criteria. The athletes were instructed to place their GSC into an envelope to blind the investigators from this information. Each test session lasted approximately 40 minutes and the order in which the participant completed the various tests was randomized. Once an athlete had been tested under one condition, he was recruited for testing in the other condition no less than 2 weeks later.

Data Reduction and Analysis

Outcome measures obtained from the SOT included an overall balance composite as well as ratio scores related to somatosensory, visual,

and vestibular balance performance. Each outcome measure was obtained from the computer printout. The ANAM yields throughput scores for each of the seven individual test modules, which were recorded for further analysis. Throughput scores represent a single outcome measure combining information for both speed and accuracy of participant responses during the test battery. The GSC was analyzed for both the total symptom score and the number of symptoms reported during each test session. The total symptom score was obtained by summing all the individual symptom scores in the GSC.

To fulfill both the primary and secondary purposes of the study, we performed a repeated-measures analysis of covariance with two covariates on each outcome measure. The covariates were: 1) the number of impacts greater than 60 g the participant had sustained since the beginning of the season and 2) the number of impacts sustained within the 7 days immediately before the test session for which they were currently evaluated. Neither the first nor the second covariate was found to be significant in any of the analyses of covariance. Subsequently, we dropped the covariates from all analyses and performed univariate within-subjects analyses of variance for each outcome variable. An alpha level of 0.05 was applied to all analyses performed using SPSS for Windows 13.0 (SPSS, Inc., Chicago, IL).

RESULTS

A total of 43 Division I collegiate football players completed the baseline and at least one follow-up test session: 22 participants completed the high testing condition and 26 participants completed the low testing condition. Fourteen participants completed both test conditions. The results we observed for measures of balance performance, neurocognitive function, and symptomatology are detailed subsequently.

TABLE 2. Means (± standard deviation), statistical test value, level of significance, and effect size for comparisons between preseason baseline and high-impact (>90 g) testing condition (n = 22)

Outcome measure	Preseason baseline	After high (>90 g) impact	F	*P* value	Effect size
Neurocognitive Function					
Simple Reaction Time 1	228.51 ± 31.64	242.13 ± 29.24	3.127	0.092	0.43
Math Processing	19.82 ± 5.30	22.85 ± 6.88	16.629	0.001[a]	0.57
Matching to Sample	38.11 ± 14.56	42.45 ± 14.05	1.471	0.239	0.30
Procedural Reaction Time	85.25 ± 16.01	104.23 ± 18.46	14.668	0.001[a]	1.19
Code Substitution	51.18 ± 11.30	53.78 ± 8.42	0.813	0.377	0.23
Sternberg Procedure	79.73 ± 13.00	86.69 ± 17.93	2.945	0.101	0.54
Simple Reaction Time 2	221.32 ± 46.11	225.75 ± 50.36	0.204	0.656	0.10
Symptomatology					
Total symptoms reported	1.50 ± 2.02	3.50 ± 3.04	10.267	0.004[a]	0.99
Total symptom score	3.41 ± 5.73	5.95 ± 6.21	2.627	0.120	0.44
Balance Performance					
Somatosensory ratio	96.93 ± 2.89	98.21 ± 3.88	2.246	0.148	0.44
Visual ratio	91.96 ± 6.28	92.11 ± 6.20	0.009	0.925	0.02
Vestibular ratio	78.18 ± 12.12	80.77 ± 9.45	0.673	0.421	0.21
Composite balance score	81.92 ± 5.27	82.33 ± 6.13	0.066	0.799	0.08

[a] Indicates significance at the 0.05 level.

TABLE 3. Means (± standard deviation), statistical test value, level of significance, and effect size for comparisons between preseason baseline and low-impact (<60 g) testing conditions (n = 26)

Outcome measure	Preseason baseline	After low (<60 g) impact	F	*P* value	Effect size
Neurocognitive Function					
Simple Reaction Time 1	239.90 ± 35.85	254.46 ± 28.66	3.204	0.086	0.41
Math Processing	21.19 ± 6.88	23.09 ± 7.48	9.797	0.004[a]	0.28
Matching to Sample	41.83 ± 12.53	49.47 ± 13.86	6.504	0.017[a]	0.61
Procedural Reaction Time	90.15 ± 18.51	100.68 ± 23.20	3.854	0.061	0.57
Code Substitution	52.92 ± 12.39	55.24 ± 9.02	0.978	0.332	0.19
Sternberg Procedure	80.06 ± 17.88	90.54 ± 21.11	5.323	0.030[a]	0.59
Simple Reaction Time 2	235.71 ± 42.21	236.82 ± 37.49	0.011	0.918	0.03
Symptomatology					
Total symptoms reported	1.73 ± 2.51	2.23 ± 2.27	0.779	0.386	0.20
Total symptom score	3.77 ± 6.54	3.50 ± 4.39	0.033	0.858	0.04
Balance Performance					
Somatosensory ratio	96.96 ± 3.02	95.66 ± 3.84	2.274	0.144	0.43
Visual ratio	92.56 ± 5.61	88.16 ± 12.04	2.866	0.103	0.78
Vestibular ratio	76.56 ± 11.41	78.44 ± 9.14	0.435	0.516	0.16
Composite balance score	81.19 ± 5.50	80.44 ± 7.68	0.191	0.666	0.14

[a] Indicates significance at the 0.05 level.

Balance Performance

Results from our balance performance assessment are provided in *Tables 2* and *3*. In assessing our primary research purpose, we did not find any statistically significant differences in any of our balance performance outcome measures after an impact of 90 *g*. This was true for all of our measures, including an overall composite score ($F_{1, 22} = 0.066$; $P = 0.799$), somatosensory ($F_{1, 22} = 2.246$; $P = 0.148$), vestibular ($F_{1, 22} = 0.673$; $P = 0.421$), and visual ($F_{1, 22} = 0.009$; $P = 0.925$) ratios. There were no observable differences in the overall composite score ($F_{1, 26} = 0.191$; $P = 0.666$), somatosensory ($F_{1, 26} = 2.274$; $P = 0.144$), vestibular ($F_{1, 26} = 0.435$; $P = 0.516$), and visual ($F_{1, 26} = 2.866$; $P = 0.103$) ratios for our second research purpose.

Neurocognitive Function

After an impact greater than 90 *g*, we observed a statistically significant increase from baseline in the Math Processing module of ANAM ($F_{1, 22} = 16.629$; $P < 0.0005$) and Procedural Reaction Time ($F_{1, 22} = 14.668$; $P < 0.0005$). As it pertained to our primary purpose, there were no observable differences in the other ANAM modules: Simple Reaction Time 1 ($F_{1, 22} = 3.127$; $P = 0.092$), Simple Reaction Time 2 ($F_{1, 22} = 0.204$; $P = 0.656$), Matching to Sample ($F_{1, 22} = 1.471$; $P = 0.239$), Code Substitution ($F_{1, 22} = 0.813$; $P = 0.377$), and Sternberg Procedure ($F_{1, 22} = 2.945$; $P = 0.101$). After a session in which a head impact no greater than 60 *g* was sustained, statistically significant differences in Math Processing ($F_{1, 26} = 9.797$; $P = 0.004$), Matching to Sample ($F_{1, 26} = 6.504$; $P = 0.017$), and

Sternberg Procedure ($F_{1, 26} = 5.323$; $P = 0.030$) modules of ANAM were observed. No discernible differences were observed in addressing our secondary purpose for the Simple Reaction Time 1 ($F_{1, 26} = 3.204$; $P = 0.086$), Simple Reaction Time 2 ($F_{1, 26} = 0.011$; $P = 0.918$), Procedural Reaction Time ($F_{1, 26} = 3.854$; $P = 0.061$), and Code Substitution ($F_{1, 26} = 0.978$; $P = 0.332$) modules of ANAM.

Symptomatology

Two subcomponents of the graded symptom checklist were analyzed; these were the total number of symptoms reported and the total severity score of symptoms reported. The total number of symptoms reported after a high-magnitude impact were statistically greater than that reported at baseline ($F_{1, 22} = 10.267$; $P = 0.004$). No differences were observed for the number of symptoms reported in the low-impact test session ($F_{1, 26} = 0.779$; $P = 0.386$). The data analysis revealed the total symptom scores did not differ statistically in either test condition (low: $F_{1, 26} = 0.033$, $P = 0.858$; high: $F_{1, 22} = 2.627$, $P = 0.120$).

DISCUSSION

The purpose of this study was to examine the effects of impact magnitude on the acute performance of balance performance and neurocognitive function in the absence of both self-reported symptoms and a clinical diagnosis of concussion 24 hours before testing. This study was the first to collect real-time data on collegiate football players and compare clinical outcome measures after high- and low-magnitude impact con-

ditions. The most important finding of our study was that non-concussed football players did not exhibit a decline in balance and cognition after an exposure in which they sustained at least one high impact ($> 90\ g$) greater than proposed theoretical injury thresholds. Most importantly, our findings suggest that clinicians should not expect a single impact greater than 90 g to necessarily result in immediate symptoms of a concussion or subsequent balance or cognitive deficits that would suggest the impact affected their overall function 24 hours later. Our findings do not support the idea that a rigid threshold for concussion can be set given that all 22 players in our high-impact condition sustained impacts well above the proposed threshold of 70 to 75 g.

A question often raised is whether or not the instrumentation in our study (the HIT System) measures head acceleration or helmet acceleration. The HIT System has been laboratory-validated at multiple test facilities against Hybrid III test dummies, which are considered to be the "gold standard" in helmet biomechanics testing. In all cases, the mean difference in linear acceleration measurements were within 8%, and as low as 2%, of Hybrid III measurements. In short, the HIT System measures head acceleration and not helmet acceleration (19). The most recent studies proposing an injury threshold have been based on video reconstruction of collisions and were not evaluated prospectively (26, 28). The threshold of 70 to 75 g reported by Pellman et al. (26) has not been confirmed using the real-time data capture used in our study. Pellman et al. also reported an average impact acceleration of $60 \pm 24\ g$ in noninjured professional football players. The first study to investigate real-time impacts in collegiate football players was conducted by Duma et al. (6); they reported an average linear acceleration of 32 ± 25 g in 38 players. They also recorded 25 impacts greater than 98 g, none of which resulted in a concussive injury, further questioning the threshold proposed by Pellman et al. Mihalik et al. (21), using similar methods, reported that players sustained impacts to the head ranging between 20 and 23 g with the highest impacts typically being recorded during practices. This information, combined with the findings from our current study, perpetuates the need for a better understanding of impact biomechanics during participation in football.

Balance Performance

According to our findings, postural stability appears to be unaffected within 24 hours of sustaining both high- and low-magnitude impacts. Performance (composite score and the three ratio scores) remained unchanged relative to preseason baseline measures. This study investigated players who did not report symptoms to the certified athletic trainer and who were not clinically diagnosed by a physician with a concussion at the time of impact. The majority of published studies have reported that balance performance is affected in athletes diagnosed with concussion and typically recovers in 3 to 5 days postinjury (10, 12, 13, 15). Because the participants in our study were not clinically diagnosed with a concussion, changes were not expected. Athletes were assigned for testing based on the magnitude of linear head acceleration sustained during a prac-

tice or game. Future studies will obviously need to investigate how exceeding proposed rotational acceleration injury thresholds might influence the postural control system.

Neurocognitive Function

Significant differences were observed between baseline and the low testing condition in Math Processing, Matching to Sample, and Sternberg Procedure. Significant improvements between baseline and the high testing condition were also noted for Math Processing and Procedural Reaction Time. The improvements in performance observed are difficult to explain. It has been reported that learning effects are found with repeated use of the ANAM battery that may cause a false sense of improvement in scores on the ANAM (17). Subjects evaluated by Levinson and Reeves (17) completed testing every 2 to 3 months as opposed to the typical serial testing that occurs in sports medicine settings. Neuropsychological test results need to be evaluated in terms of practice effects with specific considerations to the nature of the test, the time period of testing, and how many times the subject is tested (7, 11).

Symptomatology

Underreporting is a global problem when dealing with concussion (4, 7, 9, 16, 18). Our findings revealed only a slight increase in the number of symptoms reported (3.5 compared with 1.5) when comparing preseason baseline with the high-impact condition (*Table 2*). Because these measures were taken within 24 hours after the impact, one could argue that the increased symptomatology was attributed to the high-impact magnitude sustained the day before rather than acute fatigue associated with playing in the practice or game. However, in further analyzing these data, there was not a significant increase in symptom severity scores or deficit in cognition or postural stability (*Table 2*). This suggests that the average increase of two reported symptoms 24 hours after the high-impact magnitude was negligible with respect to overall performance. Likewise, the low-impact condition resulted in no statistically or clinically significant changes in symptomatology (*Table 3*). Furthermore, although we observed a slight increase of two symptoms, a mean value of 3.5 symptoms in our sample was associated with a mean total symptom score of 5.95 (see *Table 2*); this falls below previously published healthy preseason baseline total symptom scores (3, 22).

Symptoms have been shown to resolve before balance performance and neurocognitive functioning had returned to normal (3, 8, 9). Another study found that high school and collegiate football players reported fewer symptoms 5 to 7 days postinjury than they reported on their preseason baseline measures (9). Football, historically, has been known to view loss of play attributable to a concussion as a sign of player weakness. With this mentality, many inherent risks are present in this sport, especially with large numbers of participants in all levels of play in the United States. Although our findings failed to find deficits after high-magnitude impacts, clinicians should recognize that athletes may underreport symptoms; any clinician observing a "big hit" and who is suspicious a player may

be concussed should proceed with due diligence and further evaluate the athlete on the sideline.

Future Direction and Limitations to the Current Study

With real-time data, researchers can learn more about the mechanics of head impacts in football; this is also true of other helmeted sports, including ice hockey and amateur boxing. Analyzing the location of head impacts, the frequency of head impacts, and an athlete's history of concussion may play a significant role in further exploring theoretical thresholds for concussive injuries. Ongoing improvements in helmet design and tackling techniques need to be addressed as research continues to provide data to support these efforts. Underreporting concussion in football is very common and serious; ongoing research should continue to provide clinicians with more objective methods of detecting onset of concussive injuries.

Although this study was novel, a discussion of its current limitations is warranted. First, we tested athletes within 16 to 24 hours after the players had met the criteria of a given test condition. This methodology did not allow us to measure onset of effects that may have started after this initial test period; future studies should follow athletes over time to better understand the ongoing clinical manifestations of sustaining high-magnitude impacts. The timeframe used in this study falls well within common practice in athletic environments whereby testing will often be performed to assist clinicians determine whether athletes present with concussion or to rule out this pathology in the absence of symptoms, balance performance deficits, and decreases in neurocognitive function. This study also used a relatively small sample size, a limitation of the cost of this type of data collection equipment as well as athlete resources available to us. We expected the number of impacts greater than 60 g the participant had sustained since the beginning of the season and within the 7 days leading up to the session, in which they sustained an impact greater than 90 g, to affect their outcome. Our analyses suggested that this was not the case in our sample. Future studies should continue to investigate and explore this area of research; cumulative effects on repeated head trauma may cause underlying changes within athletes, potentially predisposing them to lower injury thresholds for both initial and repeat concussive injuries.

CONCLUSION

It has been long thought that a hard hit to the head often results in concussion-like symptoms; however, our study suggests that the magnitude alone cannot be considered a reliable predictor of how an athlete will present with respect to acute clinical outcomes. Our study was conducted in an attempt to determine the efficacy of using helmet telemetry to identify concussion and/or concussion-like signs and symptoms in the absence of subjective information provided by the athlete. The results of this study revealed no deficits (relative to preseason baseline measures) after either of the two impact magnitude conditions, thus refuting our research

hypotheses that high-magnitude impacts would yield deficits in balance performance and neurocognitive function. Our study, which used real-time data collection techniques, raises questions about earlier laboratory-based impact reconstruction data and the proposed theoretical injury thresholds that resulted from them.

REFERENCES

1. Centers for Disease Control and Prevention (CDC): Sports-related recurrent brain injuries—United States. **MMWR Morb Mortal Wkly Rep** 46:224–227, 1997.
2. Cernich A, Reeves D, Sun W, Bleiberg J: Automated Neuropsychological Assessment Metrics sports medicine battery. **Arch Clin Neuropsychol** 22 [Suppl 1]:S101–S114, 2007.
3. Collins MW, Grindel SH, Lovell MR, Dede DE, Moser DJ, Phalin BR, Nogle S, Wasik M, Cordry D, Daugherty KM, Sears SF, Nicolette G, Indelicato P, McKeag DB: Relationship between concussion and neuropsychological performance in college football players. **JAMA** 282:964–970, 1999.
4. Collins MW, Hawn KL: The clinical management of sports concussion. **Curr Sports Med Rep** 1:12–22, 2002.
5. DiMasi F: *Transformation of Nine-Accelerometer-Package Data for Replicating Head Kinematics and Dynamic Loading*: *Technical Report*. Washington, DC, U.S. Department of Transportation, National Highway Traffic Safety Administration, 1995.
6. Duma SM, Manoogian SJ, Bussone WR, Brolinson PG, Goforth MW, Donnenwerth JJ, Greenwald RM, Chu JJ, Crisco JJ: Analysis of real-time head accelerations in collegiate football players. **Clin J Sport Med** 15:3–8, 2005.
7. Echemendia RJ, Julian LJ: Mild traumatic brain injury in sports: Neuropsychology's contribution to a developing field. **Neuropsychol Rev** 11:69–88, 2001.
8. Echemendia RJ, Putukian M, Mackin RS, Julian L, Shoss N: Neuropsychological test performance prior to and following sports-related mild traumatic brain injury. **Clin J Sport Med** 11:23–31, 2001.
9. Field M, Collins MW, Lovell MR, Maroon J: Does age play a role in recovery from sports-related concussion? A comparison of high school and collegiate athletes. **J Pediatr** 142:546–553, 2003.
10. Gagnon I, Friedman D, Swaine B, Forget R: Balance findings in a child before and after a mild head injury. **J Head Trauma Rehabil** 16:595–602, 2001.
11. Grindel SH, Lovell MR, Collins MW: The assessment of sport-related concussion: The evidence behind neuropsychological testing and management. **Clin J Sport Med** 11:134–143, 2001.
12. Guskiewicz KM: Postural stability assessment following concussion: One piece of the puzzle. **Clin J Sport Med** 11:182–189, 2001.
13. Guskiewicz KM: Assessment of postural stability following sport-related concussion. **Curr Sports Med Rep** 2:24–30, 2003.
14. Guskiewicz KM, Riemann BL, Perrin DH, Nashner LM: Alternative approaches to the assessment of mild head injury in athletes. **Med Sci Sports Exerc** 29 [Suppl]:S213–S221, 1997.
15. Guskiewicz KM, Ross SE, Marshall SW: Postural stability and neuropsychological deficits after concussion in collegiate athletes. **J Athl Train** 36:263–273, 2001.
16. Kaut KP, DePompei R, Kerr J, Congeni J: Reports of head injury and symptom knowledge among college athletes: Implications for assessment and educational intervention. **Clin J Sport Med** 13:213–221, 2003.
17. Levinson DM, Reeves DL: Monitoring recovery from traumatic brain injury using Automated Neuropsychological Assessment Metrics (ANAM V1.0). **Arch Clin Neuropsychol** 12:155–166, 1997.
18. Lovell MR, Collins MW: Neuropsychological assessment of the college football player. **J Head Trauma Rehabil** 13:9–26, 1998.
19. Manoogian S, McNeely D, Duma S, Brolinson G, Greenwald R: Head acceleration is less than 10 percent of helmet acceleration in football impacts. **Biomed Sci Instrum** 42:383–388, 2006.
20. McCrea M, Guskiewicz KM, Marshall SW, Barr W, Randolph C, Cantu RC, Onate JA, Yang J, Kelly JP: Acute effects and recovery time following concussion in collegiate football players: The NCAA Concussion Study. **JAMA** 290:2556–2563, 2003.

21. Mihalik JP, Bell DR, Marshall SW, Guskiewicz KM: Measurement of head impacts in Division I football players: An investigation of positional and event-type differences. **Neurosurgery** 61:1229–1235, 2007.
22. Mihalik JP, Stump JE, Collins MW, Lovell MR, Field M, Maroon JC: Posttraumatic migraine characteristics in athletes following sports-related concussion. **J Neurosurg** 102:850–855, 2005.
23. Mueller FO: Sports related head and brain trauma. **N C Med J** 62:368–372, 2001.
24. Padgaonkar AJ, Krieger KW, King AI: Measurement of angular acceleration of a rigid body using linear accelerometers. **J Appl Mech** 42:552–556, 1975.
25. Patel AV, Mihalik JP, Notebaert AJ, Guskiewicz KM, Prentice WE: Neuropsychological performance, postural stability, and symptoms after dehydration. **J Athl Train** 42:66–75, 2007.
26. Pellman EJ, Viano DC, Tucker AM, Casson IR, Waeckerle JF: Concussion in professional football: Reconstruction of game impacts and injuries. **Neurosurgery** 53:799–814, 2003.
27. Woodard JL, Marker CD, Tabanico FE, Miller SK, Dorsett ESW, Cox LR, Gould F, Bleiberg J: A validation study of the Automated Neuropsychological Assessment Metrics (ANAM) in non-concussed high school football players. **J Int Neuropsychol Soc** 8:175, 2002.
28. Zhang L, Yang KH, King AI: A proposed injury threshold for mild traumatic brain injury. **J Biomech Eng** 126:226–236, 2004.

Acknowledgments

COMMENTS

This intriguing study by McCaffrey et al. evaluated acute balance and neurocognitive effects in 43 collegiate football players using accelerometer data to register impact magnitudes. The design was well considered, double-blinded, and used the real-time Automated Neuropsychological Assessment Metrics battery for neurocognitive testing and the sensory organization test for balance measurement. A graded system checklist was used for clinical athlete assessment.

Contrary to previous studies, they found that a simple impact of magnitude greater than 90 g did not necessarily result in a clinical concussion. Thus, a defined concussion threshold can not be established, and once again we find that identification of the athlete with mild traumatic brain injury remains, at times, elusive. The authors correctly point out that underreporting, or underdiagnosing concussion remains a common occurrence. Acceleration data provided by telemetry will allow us to continue to refine our understanding of concussion and head impact in sports. It remains to be seen what ultimate role it will play.

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With increasing awareness of the potential risks for multiple concussion in organized athletics, novel bioengineering instrumentation is being used to gather data. This article reports the use of a head-impact telemetry system using six separate accelerometers placed within football helmets to observe whether the magnitude of head impact can be correlated with balance and neurocognitive performance. Using a threshold impact of 90 g, athletes were evaluated to see whether this was a critical threshold level associated with concussion and balance abnormality as tested on the sensory organization test. The authors list several limitations of the study, including small subject number, the inability to measure the onset of abnormalities earlier after a blow to the head, and the need for future studies that possibly use neurocognitive tests that require less of a learning- or practice-effect limitation.

Regardless, McCaffrey et al. report that there is no reliable high-impact force that unequivocally results in concussive findings. In other words, a single impact greater than 90 g did not necessarily result in symptoms or signs of a cerebral concussion. Their findings indicate that, at least presently, a rigid threshold that would result in a concussion in terms of g forces is not known. In other words, a single seemingly devastating blow to the head as often shown repeatedly on football replays may not be associated with significant neurocognitive or postural abnormalities. On the contrary, at times, or as we know clinically, blows that did not seem to have the same forces may result in significant cognitive abnormalities. Obviously, rotational forces, linear acceleration, helmet fit, helmet type, and many other factors are operant in sports concussive episodes. This article points out that a single impact of more than 90 g does not necessarily result in immediate symptoms of concussion. Additional corroborative studies are needed, perhaps using other accelerometer systems, such as those used to study high-speed race car drivers.

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McCaffrey et al. present initial real-time data on college football players who are compared on clinical outcome after high- and low-magnitude impacts. Data obtained from this study indicate that the proposal of Pellman et al. (1) that there is a 70 to 75 g concussion threshold is inaccurate. It is noted that the authors used a well-designed, double-blind, repeated-measures study. In addition, they investigated impact threshold by assessing both acute balance and neurocognitive performance after head impact. The authors validly conclude that proposed theoretical injury thresholds obtained from earlier laboratory-based impact-reconstruction studies need to be questioned. Overall, this study increases the knowledge base of sports-related head trauma.

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1. Pellman EJ, Viano DC, Tucker AM, Casson IR, Waeckerle JF: Concussion in professional football: Reconstruction of game impacts and injuries. **Neurosurgery** 53:799–814, 2003.

Although athletes did exhibit an increase in symptoms from pre-collision baseline data, no significant differences on the balance assessment or the Automated Neuropsychological Assessment Metrics battery were evident. This study is well conceived, and it provides a potentially useful model for studying the relationship between collision forces and clinical outcomes. It is difficult to interpret these findings for several reasons. First, the number of subjects included in the study is small, which makes statistical analysis tenuous. Second, although the authors suggest that no significant differences were likely, given that the athletes were not diagnosed as having suffered concussion, it may be that the lack of an effect for the Automated Neuropsychological Assessment Metrics battery is secondary to the large practice effects from the athletes taking this test battery several times. Therefore, this study does little to provide validation data for the Head Impact Telemetry system. I am hopeful that their continued research in this area will lead to more convincing data.

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