Effect of subconcussive impacts on functional outcomes over a single collegiate football season

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Abstract
Context: In collision sports, particularly American football, athletes can accumulate thousands of subconcussive impacts, or head acceleration events (HAEs), across a single season; however, the short-term consequences of these impacts are not well understood.

Objective: To investigate the effects of the accumulation of impacts during practices on cognitive functions over a single football season.

Design: Prospective observational study.

Setting: Athletic training room and University laboratory.

Participants: Twenty-three NCAA Football Bowl Subdivision players.

Main outcome measures: Helmet accelerometers during practices and virtual reality testing (VR; balance, reaction time, spatial memory) before and after the season.

Results: Preseason had the majority of ≥80 G impacts while during the season had the majority of ≥25 G to <80 G impacts and positional differences showed that linemen had the majority of both types. Virtual reality analysis revealed that scores significantly decreased after the season for spatial navigation (p < 0.05) but not for balance or reaction time. Significant correlations (p < 0.05) were found between cognitive measures and player demographic variables.

Conclusions: Even in the absence of clinical symptoms and concussion diagnosis, repetitive impacts may cause cognitive alterations. Documenting the distribution of impact quantity and intensity as a function of time and position may be considered by coaches and clinicians to reduce the accumulation of impacts in athletes exposed in contact sports.

Keywords
Subconcussive impacts, head acceleration events, accelerometer, virtual reality, football

Introduction
Repetitive subconcussive impacts, or head acceleration events (HAEs), are impacts that involve the transfer of mechanical energy to the brain with sufficient force to injure axonal or neuronal integrity but do not result in clinical symptoms.1,2 These impacts are often unmanaged or undiagnosed, as they are less severe than a full-blown concussive injury, and result in no immediate neurological deficits, making them challenging to operationally define.3 A recent review by Mainwaring and colleagues4 found no consensus definition in use for these impacts. Despite this, there has been growing concern surrounding these impacts as they can accrue to large numbers over the course of a season or career5,6 and have a possible link to neurological impairments.6 Post-mortem studies, done in both humans and animals, support the notion that repeated HAEs may have an accumulative effect7 and affect cognitive processes.8 The link between repetitive HAEs and cognitive function,9–12 white matter changes on

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diffusion tensor imaging (DTI), alterations of cerebral blood flow, functional brain alterations, and cerebral spinal fluid changes have been previously demonstrated. However, the intensity and frequency of the impacts necessary to cause damage is still unknown. 

Players of collision sports, such as football, are at a high risk for the accumulation of repetitive head impacts. Previous studies have shown that high school football players can average 600 impacts over a season and collegiate players average 1000 impacts. However, these exposures can also vary based on player position and previous concussive history. Research has begun to link these exposure metrics to cognitive and neurobehavioral disturbances, including increased risk for Alzheimer’s disease, chronic traumatic encephalopathy (CTE), or amyotrophic lateral sclerosis (ALS). However, there is still much debate regarding the progression of these disturbances and their link to repetitive impacts.

Accelerometers are now commonly used in research to track the number of HAEs in American football. College football players (compared to high school football and other college sports) experience the most impacts across a season, the highest average peak linear and rotational acceleration per impact, and the highest cumulative linear and rotational acceleration per impact. The type of practice is also a contributing factor to the number of occurring impacts. Full-pad practices have been shown to have the highest number of impacts per session and these numbers increase in game settings.

Position played is a major confounding factor and current literature suggests that offensive and defensive linemen sustain the greatest number of impacts, at a lower magnitude however, than other positions, as they are normally on the line of scrimmage and are involved in short distance, low magnitude impacts on almost all plays. Athletes in the skill or speed positions while running back, fullback, tight end, corner back, safety, and linebacker; players that often build up momentum prior to tackling or being tackled. Playing position also included imaging data which has been previously published. All participants provided informed written consent, as approved by the Penn State University Institutional Review Board (IRB#2907) and were compensated for their involvement in the study. It is important to note that none of the participants included in this study were diagnosed with a concussion by medical personnel during the course of the season.

Methods

Design: Before the season started, all participants underwent a baseline test on virtual reality and the accelerometer BodiTrak system was installed in their helmets. Once preseason began, participants wore their accelerometers during 53 practice sessions. After the season ended, all participants were tested again on the virtual reality system (see Procedures below for details on the specific modalities).

Participants: 24 participants were recruited and enrolled in the study. 1 participant dropped out during baseline testing, so their data was not used and the sample size moving forward was n=23. All participants (n=23) were Penn State University NCAA Football Bowl Subdivision football players. Background information is contained in Table 1. These participants were part of a larger study that also included imaging data which has been previously published. All participants provided informed written consent, as approved by the Penn State University Institutional Review Board (IRB#2907) and were compensated for their involvement in the study. It is important to note that none of the participants included in this study were diagnosed with a concussion by medical personnel during the course of the season.

Procedures

BodiTrak System: Impacts to the head for all participants were monitored using helmet sensors from the
Head Health Network BodiTrak system. These sensors, created by Vista Medical, were adapted to be individually placed inside each individual participant’s helmet using a 3M VHB adhesive and are comprised of elastic fabric with pressure monitors and impact sensors. With sensor installation, the sensors are placed directly on the inner surface of the helmet between the shell and the padding and the helmet is not altered in any way. All sensors were placed by a certified athletic trainer (author M.S.) who was trained on proper installation techniques and the sensors were monitored throughout the season for integrity and functionality. The sensors provide estimates on linear acceleration (in units of G) and location of impact and were in place throughout the season. Impacts were only recorded during practices (not games) for a total of 53 possible sessions.

Virtual Reality System: A 3D TV system (HeadRehab.com) with a head mounted accelerometer was used. The accelerometer is attached to an adjustable headband which each participant wore over their left ear. Data were collected before season (baseline) and after the season. Three different modules were used: balance, reaction time, and spatial memory (see 36–38 for reliability and validity of all modules for use in detecting sport-related concussion. Briefly: spatial memory (sensitivity 95.8%/specificity 91.4%); reaction time (sensitivity 95.2%/specificity 89.1%); balance (sensitivity 85.7%/specificity 87.8%)). In the balance task, participants are instructed to hold tandem Romberg position for all trials. In the first trial, the virtual room (Figure 1) is completely still (for a baseline measure) and in the subsequent 6 trials, the virtual room moves in various directions. The system measures the position and orientation in yaw, pitch, and roll directions. In the reaction time module, participants are instructed to stand feet shoulder width apart, hands on their hips. The virtual room moves, and they are instructed to move their body in the same direction as the virtual room. The system measures both reaction time (in ms) and errors of anticipation (wrong direction of response). In the spatial memory module, participants are shown a 3D randomized representation of a virtual corridor. They are shown a pathway with multiple turns to a door and then the return trip. Afterwards, they are instructed to repeat the exact pathway using a joystick. The system measures how many errors it takes to get to the door and the total time to complete the task. Raw data were analyzed using SideLine v10.1 test reporting module which uses mathematical algorithms to produce a score on a scale of 0 (fail) to 10 (perfect) and this score was used for analysis.

Statistical Analysis: All statistical analyses were performed using SPSS V25. For all analyses, statistical significance was considered reached at $p < 0.05$. Normality of the VR data was assessed using histogram plots and the Shapiro-Wilk test. Due to non-normality, a Wilcoxon Signed Rank Test was used to assess differences in virtual reality scores before the season versus after the season. Additionally, participants were grouped into categories of concussion history (i.e., yes or no) or position categories (i.e, speed (quarterback, running back, halfback, fullback, wide receiver, tight end, defensive back, safety, and linebacker) or non-speed (offensive and defensive linemen) based off of Lehman’s classifications 23) and then differences in virtual reality scores before the season versus after the season were also examined. Point-Biserial correlations were used, given the ability to measure the association between continuous and dichotomous variables, to assess the relationship between accelerometer data, virtual reality data, and participant demographic information. Impacts were categorized into categories

| Table 1. Participant demographic information. |
|-----------------------------------------------|
| Variables                                      |
| Demographics, range (M ± SD)                  |
| Age                                           |
| Number of Years Playing                        |
| Number of Previous Concussions, n (%)         |
| 0                                             |
| 1                                             |
| 2                                             |
| ADHD Diagnosis, n (%)                         |
| Psychiatric Diagnoses, n (%)                  |
| Position Breakdown, n (%)                     |
| Offensive Line                                |
| Defensive Line                                |
| Tight End                                     |
| Linebacker                                    |
| Safety                                        |
| Running Back                                  |
| Variables (n = 23)                            |
| Demographics, range (M ± SD)                  |
| Age 19–23 (20.78 ± 1.28)                      |
| Number of Years Playing 6–19 (10.89 ± 3.34)   |
| Number of Previous Concussions, n (%)         |
| 0 14 (60.9)                                   |
| 1 7 (30.4)                                    |
| 2 2 (8.7)                                     |
| ADHD Diagnosis, n (%)                         |
| Psychiatric Diagnoses, n (%)                  |
| Position Breakdown, n (%)                     |
| Offensive Line                                |
| Defensive Line                                |
| Tight End                                     |
| Linebacker                                    |
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| Position Breakdown, n (%)                     |
| Offensive Line                                |
| Defensive Line                                |
| Tight End                                     |
| Linebacker                                    |
| Safety                                        |
| Running Back                                  |

![Figure 1. Representation of the virtual room.](image-url)
of $\geq 80 \text{G}$ (to reflect higher intensity impacts) and $\geq 25 \text{G} < 80 \text{G}$ (to reflect lower intensity impacts) based on work done by Mihalik\textsuperscript{20} and on pilot work done at Penn State. Correction for multiple comparisons was done on correlation analyses for the individual virtual reality components as each modality (balance, reaction time, or spatial memory) was a unique hypothesis ($p = 0.05/6 = 0.0083$).

Results

**Accelerometer Data:** A total of 129 impacts at $\geq 80 \text{G}$ were recorded across the season (53 sessions) with 78.3\% (101 impacts) occurring during the preseason (13 sessions) and 21.7\% (28 impacts) occurring during the regular season (40 sessions). A total of 3557 impacts at $\geq 25 \text{G} < 80 \text{G}$ were recorded across the season with 32.6\% (1158 impacts) occurring during the preseason and 67.4\% (2399 impacts) occurring during the regular season. The raw number of individual impacts at $\geq 80 \text{G}$ and $\geq 25 \text{G} < 80 \text{G}$ obtained over the season are presented in Table 2. The average incidence rate for impacts at $\geq 80 \text{G}$ across the season was $0.0047 \pm 0.0038$ while the average incidence rate for impacts $\geq 25 \text{G} < 80 \text{G}$ across the season was $0.1228 \pm 0.0878$.

By practice type, full pads had the highest raw cumulative number of $\geq 80 \text{G}$ (78) impacts followed by scrimmages (30), upper pads only (19) and then helmets only (2). For the $\geq 25 \text{G} < 80 \text{G}$ impacts by practice type, full pads have the highest raw cumulative number (1934) followed by upper pads only (1225), scrimmages (300), and then helmets only (98). However, practice type rate showed that the scrimmage practices had the highest average number of impacts per practice followed by full pads, uppers, and lastly, helmets.

**Virtual Reality Data:** Virtual reality results were produced on a scale of 0 (fail) to 10 (perfect) for each module: spatial memory, balance, and reaction time. Average scores for the before season and after season were calculated for all 23 participants and Wilcoxon Signed Rank Test were run (significance, $p < 0.05$). In the spatial memory module, a significant change ($Z = -2.160$, $p = 0.03$, effect size $r = 0.45$) in score from before season ($M = 8.79$, $SD = 1.90$) to after season ($M = 7.74$, $SD = 2.85$) was observed. In the balance module, there was a non-significant change ($Z = -1.02$, $p = 0.31$, $r = 0.21$) in scores from before season ($M = 2.5$, $SD = 1.2$) to after season ($M = 2.0$, $SD = 1.1$) was observed. In the reaction time module, there was a non-significant change ($Z = -0.45$, $p = 0.65$, $r = 0.11$) in scores from before season ($M = 7.5$, $SD = 2.5$) to after season ($M = 7.0$, $SD = 2.4$) was observed.

Table 2. Accelerometer data for all participants ($n = 23$) including position information.

| Participant number | Position     | Monitored sessions (53 total) | Total $\geq 80 \text{G}$ | Incidence rate of $\geq 80 \text{G}^a$ | Total $\geq 25 \text{G}$ and $< 80 \text{G}$ | Incidence rate of $\geq 25 \text{G}$ and $< 80 \text{G}^a$ |
|--------------------|--------------|-----------------------------|--------------------------|------------------------------------------|-----------------------------------------------|--------------------------------------------------|
| 1*                 | Tight End    | 27                          | 0                        | 0.0000                                   | 17                                            | 0.0139                                           |
| 2                  | Offensive Line | 42                          | 3                        | 0.0025                                   | 95                                            | 0.0779                                           |
| 4                  | Defensive Line | 37                          | 5                        | 0.0041                                   | 116                                           | 0.0952                                           |
| 5                  | Defensive Line | 38                          | 7                        | 0.0057                                   | 180                                           | 0.1477                                           |
| 6                  | Safety        | 45                          | 5                        | 0.0041                                   | 101                                           | 0.0829                                           |
| 7                  | Defensive Line | 47                          | 11                       | 0.0090                                   | 148                                           | 0.1214                                           |
| 8                  | Offensive Line | 47                          | 10                       | 0.0082                                   | 455                                           | 0.3733                                           |
| 9*                 | Offensive Line | 26                          | 0                        | 0.0000                                   | 28                                            | 0.0230                                           |
| 10                 | Offensive Line | 49                          | 15                       | 0.0123                                   | 344                                           | 0.2822                                           |
| 11                 | Offensive Line | 30                          | 5                        | 0.0041                                   | 221                                           | 0.1813                                           |
| 12                 | Running Back  | 43                          | 13                       | 0.0107                                   | 110                                           | 0.0902                                           |
| 13                 | Safety        | 51                          | 2                        | 0.0016                                   | 124                                           | 0.1017                                           |
| 14                 | Defensive End | 37                          | 4                        | 0.0033                                   | 155                                           | 0.1272                                           |
| 15                 | Defensive End | 32                          | 7                        | 0.0057                                   | 95                                            | 0.0779                                           |
| 16**               | Defensive Line | 2                           | 2                        | 0.0016                                   | 9                                             | 0.0074                                           |
| 17                 | Defensive Line | 36                          | 2                        | 0.0016                                   | 99                                            | 0.0812                                           |
| 18                 | Defensive Line | 47                          | 2                        | 0.0016                                   | 74                                            | 0.0607                                           |
| 19                 | Offensive Line | 38                          | 1                        | 0.0008                                   | 183                                           | 0.1501                                           |
| 20                 | Linebacker    | 45                          | 1                        | 0.0008                                   | 151                                           | 0.1239                                           |
| 21                 | Offensive Line | 48                          | 7                        | 0.0057                                   | 301                                           | 0.2469                                           |
| 22                 | Tight End     | 37                          | 13                       | 0.0107                                   | 205                                           | 0.1682                                           |
| 23**               | Linebacker    | 17                          | 12                       | 0.0098                                   | 83                                            | 0.0681                                           |

Players who missed part of the season due to a non-neurological injury are indicated by an asterisk (*). Players whose season ended early due to non-neurological injury are indicated by a double asterisk (**).

$^a$Incidence rate calculated as: (number of impacts)/(population size$\times$time of study). For example, for participant 1: $17/(23\times53)$. 
season (M = 7.89, SD = 2.49) to after season (M = 8.97, SD = 0.74). The reaction time module also showed a non-significant change (Z = −1.40, p = 0.16, r = 0.29) in score from before season (M = 4.78, SD = 3.30) to after season (M = 5.98, SD = 2.18).

Additionally, when data was examined based on previous concussion history (yes or no) there were significant differences found. Players with a previous history of concussion (n = 9) had a significant decrease (Z = −2.016, p = 0.04) in the spatial memory module from before the season (M = 9.03, SD = 1.12) to after the season (M = 6.44, SD = 3.19). No other significant differences were found for either group in the other VR modules.

**Correlation Data:** Point-Biserial Correlations were run between predictors of interest (position category, years played football, and how many previous concussions) and main outcomes (before and after VR scores and impacts) and are presented in Table 3. After correction for multiple comparisons, only non-speed versus speed position category was significantly negatively correlated with before the season spatial memory VR scores.

### Discussion

To our knowledge, this study is the first to explore neurocognitive changes, via VR measures, after a single season of football. By implementing testing throughout the season, we were able to begin to track players’ neurocognitive abilities and how it relates to the accumulation of impacts. This study revealed several findings of interest that will be discussed in the following text.

In terms of raw accelerometer data, first, preseason practices contained the vast majority of the high impacts (≥80 G). Second, practice type influenced the cumulative number of impacts received. Full pads had the highest raw number of impacts both at ≥80 G and at ≥25 G to <80 G, which has been previously demonstrated. Third, speed players (tight end, linebacker, defensive back, running back) experienced more cumulative impacts at ≥80 G and non-speed players (linemen) had more cumulative impacts at ≥25 G to <80 G, which has been previously demonstrated.

An athletic trainer, physician, or sport coach using this technology can monitor impacts in real time, referring back to specific time points, drills, or injury instances. They can assess whether or not a certain drill is causing too many head impacts, or if an instructed movement technique is exposing the head to increased risk of trauma. Furthermore, coaches may be able to draw conclusions about how to structure practices, whether to include certain drills, or whether certain players need revisions to their techniques.

Virtual reality data revealed a significant decrease in spatial memory scores from before the season to after the season (p < 0.05) as well as no significant change in balance and reaction time scores. Furthermore, when players were separated into groups based on previous concussion diagnosis (yes or no), only players with previous history of concussion had significant decreases in spatial memory scores after the season (p < 0.05). Cognitive impairments have been previously demonstrated, mostly in MRI studies, showing visual working memory impairments being associated with altered activation in the dorsolateral prefrontal cortex (DLPFC) and decreases in cortical thickness. This study shows impairments in memory without the use of advanced MRI suggesting potential utility as a measure of memory when MRI may not be feasible. It also highlights the importance of spatial memory as a beneficial and low cost (both in a sense of time and money compared to other common research modalities) test for detecting neurocognitive changes as a function of cumulative impacts that players experience over a single football season in the absence of diagnosed concussion.

The correlation analyses also revealed findings of interest. Non-speed versus speed position category was significantly negatively correlated with before-season spatial memory VR score, with non-speed players having higher before the season spatial memory score. These correlations suggest that in the future, spatial memory assessment could be a critical clinical tool in determining which players may be at risk for

### Table 3. Point-biserial correlations.

|                    | Before spatial | Before balance | Before Rxn time | Post spatial | Post balance | Post Rxn time |
|--------------------|---------------|---------------|-----------------|--------------|--------------|--------------|
| Non-Speed vs Speed | −0.537**      | 0.123         | 0.111           | −0.367       | 0.122        | 0.107        |
| Years Played       | −0.019        | −0.046        | 0.283           | −0.283       | −0.211       | −0.107       |
| How Many Cx        | 0.008         | 0.072         | 0.083           | −0.282       | −0.175       | 0.043        |
| Total 80 G         | −0.095        | 0.068         | −0.096          | 0.061        | −0.143       | −0.159       |
| Total 25 G         | −0.123        | 0.089         | 0.230           | 0.197        | −0.013       | −0.311       |

cx = concussion; Total 80 G = impacts ≥80 G; Total 25 G = impacts ≥25 G to <80 G; Before = before season; rxn time = reaction time; Post = after season.

**Correlation is significant after correction for multiple comparisons.
cognitive deficits throughout the season and that monitoring players’ neurocognitive function during the entire season, even in the absence of any clinical symptoms, may be an important injury prevention approach.

The information from this study could potentially help identify players at risk for high number of repetitive head impacts and cognitive deficits, as previous literature has shown links between concussion history and cognitive functioning. Retired professional football players, diagnosed with three or more concussions, were found to report more cognitive symptoms, specifically memory impairment and cognitive impairment, than retired players with no history of concussion. Our finding of a cognitive decline from before the season to after the season are in line with previous reports that a history of concussions in college football players may result in lower cognitive functions including memory changes. However, simply examining players before and after the season for deficits could potentially be misleading. These pre to postseason changes seem to provide support for the notion that clinical symptoms are not a necessary observation for the presence of deficits in brain functioning. However, it is still unclear if these changes could be a compensatory adaptation to cumulative impacts or a more lasting alteration of brain functional integrity.

This study is not without limitations. The present study was based on a fairly small cohort of football players so future work should try to replicate these findings in larger sample sizes, as well as examine a greater variety of players (including females). Additional during-season cognitive testing would also prove beneficial as testing on a variety of cognitive and functional tasks could also further increase understanding of changes within a season. Furthermore, only practice accelerometer data, and not game data, was used collected which could confound the results. Future studies should examine these sessions as well as there is potential for higher overall number of impacts, especially the impacts at higher intensities. Lastly, there is concern over the use of accelerometers in contact sports due to the accuracy of the systems used. Forces measured by the helmet systems may not accurately represent the forces experienced by the brain itself. The system used in this study likely has inconsistencies in forces measured and margins of error like many other systems used in research. Additionally, incorporating new technologies along with virtual reality could lead to the development of more beneficial assessment tools than currently used in clinical practice.

Conclusion and clinical implications

Presently, the medical community does not have proven quantitative measures to diagnose concussions, nor any proven measures to predict an individual’s susceptibility to concussive and subconcussive injury. The quantitative data regarding impacts obtained in practices via helmet sensors throughout the football season allowed us to assign an objective value to individual events that had previously only been assessed subjectively. This information, combined with the results from the virtual reality testing, may allow coaches and policymakers to more confidently embrace the idea that minimizing the number and intensity of head impacts will benefit the participant and prevent decreased cognitive testing scores after participating in one football season.

No exact diagnostic testing for concussion exists as of yet and the accelerometer technology should not be used as a diagnostic measure. However, medical professionals may be able to use technologies such as virtual reality and helmet sensors to assist in making decisions about the health and well-being of patients. Until the medical community has found definitive diagnostic measures for concussive and/or subconcussive injuries, these technologies could be used as another tool to assist in making more informed decisions about patient safety.

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Data availability statement

Data is available upon reasonable request to the authors.

Declaration of conflicting interests

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Supplemental Material

Supplementary material for this article is available online.
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