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The Effects of Subconcussive Impacts on Postural Stability

Eric Shiflett

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THE EFFECTS OF SUBCONCUSSIVE IMPACTS ON POSTURAL STABILITY IN DIVISION I FOOTBALL ATHLETES

by

Eric Drew Shiflett

(under the direction of Barry Munkasy)

ABSTRACT

Context: The effects of concussions on postural stability, both acutely and chronically, have been well studied and noted. However, whether subconcussive impacts lead to these same impairments has not been heavily investigated. **Objectives:** The primary purpose of this study was to examine the effects of subconcussive impacts on postural stability in NCAA Division I football athletes. We hypothesized that both the subconcussive (SUBC) group and the control (CONT) group would show declines in postural stability following a single fall season. We also hypothesized that there would be no significant differences between SUBC and CONT from preseason to postseason for Balance Error Scoring System total score and Approximate Entropy (ApEn) values. The secondary purpose was to predict deficits in postural stability based on cumulative linear acceleration, cumulative rotational acceleration, total number of impacts, and Head Injury Criterion (HIC). We hypothesized that the total number of impacts and cumulative linear acceleration would predict significant changes in postural stability. **Design:** This was a prospective longitudinal study. **Setting:** The Georgia Southern University Biomechanics Laboratory. **Participants:** 15 NCAA Division 1 collegiate football players were instrumented with the Head Impact Telemetry System (HITS) and 13 non-contact athletes with a fall season were recruited for control participants. **Intervention:** The 2014 fall football season. **Results:** No clinically significant deficits in postural stability were measured over the course of a single season. There was an increase in ApEn in the anteroposterior direction for left leg stance in both groups and in the mediolateral direction for double leg stance in SUBC over time. **Conclusion:** The results of this study show no deficits across a single athletic season. However, caution should still be taken as there is literature supporting late-life detriments due to brain trauma.

INDEX WORDS: Subconcussive, Head Impact Telemetry System, postural stability, static stance, BESS, gait, dual task, approximate entropy

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by

Eric Drew Shiflett, ATC, LAT, CISSN

B.S., University of Mount Union, 2013

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in

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by

Eric Drew Shiflett, ATC, LAT, CISSN

Major Professor:	Barry Munkasy
Committee:	Barry Joyner
	Thomas Buckley
	Nicholas Murray

Electronic Version Approved:

Spring 2015

DEDICATION

I dedicate this project and process to my family. Without them, I would not be the person I am today and would not have had the strength to persevere and accomplish all that I have. I also would like to make a special dedication to my late mentor, Daniel M. Gorman. Without his influence, I would not be an Athletic Trainer, nor would I have gone on to the Graduate level. You are sorely missed, but your teachings live on through those you have touched. Thank you, Dan!

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CHAPTER 1

INTRODUCTION

Concern regarding the effects of head impacts, both concussive and subconcussive, has rapidly increased. Each year, 1.6 to 3.8 million sport related concussions occur in the United States.¹ Impairments following a concussion have been widely investigated by researchers around the world. However, little is known about the effects of subconcussive impacts. A subconcussive impact is a blow to the head that does not result in a clinical diagnosis of a concussion.² These hits to the head have the potential to lead to lifelong neurological impairments. Repeat exposure to subconcussive impacts can be linked to pathologically altered neurophysiology, cognitive function, and physiological changes in the brain.³⁻⁶ Gait and static postural stability are known to have deficits following a concussion.⁷⁻¹⁸ This investigation looks at measures of gait and static stance to determine if non-concussive impacts over the course of a single football season show these same deficits.

The effects of subconcussive impacts remain conflicted.^{5,19-22} Retired National Football League (NFL) players with a history of 3 or more concussions have an increased likelihood of suffering from late-life difficulties such as: mild cognitive impairment depression, and Alzheimer's Disease.^{23,24} However, unlike concussions, there is no established assessment tool or battery for examining the potential effects of subconcussive impacts. To date, a number of investigators have utilized typical concussion assessment techniques to attempt to measure impairments of subconcussive blows.^{19,20,22} One investigation observed differences in neuropsychological measures between contact and non-contact athletes.²⁵ This study showed that a higher percentage of contact athletes performed worse than predicted on neuropsychological testing when compared to non-contact athletes. These decreases in performance were predicted

by impact exposure metrics such as: mean number of impacts per athlete, max linear acceleration, and max rotational acceleration. In particular, reaction time was seen to be slower in contact athletes when compared to non-contact athletes. This significant difference was then predicted by peak linear acceleration with a regression analysis.²⁵ This suggests that there may be a subgroup of individuals that have learning and memory deficits due to repetitive exposure to head impacts.²⁵ A different investigation by Volberding et al. also showed that football athletes had a slower reaction time over the course of a single season.⁶ The authors proposed that this could be due to repetitive head impacts sustained during the season. These impacts may be causing damage to areas of the brain, such as the cerebral cortex, which are presented as worsened reaction time and verbal memory scores.⁶

Studies have also investigated the effects of subconcussive head impacts on brain function through imaging techniques.^{19,26} Functional Magnetic Resonance Imaging measures brain activity based on the blood oxygenation level dependent effect. Blood flow to an area of the brain increases with activity. It is able to detect oxygenated blood levels since blood gives a stronger magnetic signal when it is oxygen-rich.²⁷⁻²⁹ In the course of a single season, high school football athletes with no clinical signs of a concussion showed visible changes in Functional Magnetic Resonance Imaging.¹⁹ Athletes that may or may not exhibit functional signs of a concussion (i.e. symptoms, postural stability, cognition, and/or neuropsychology as determined by a clinician) also showed visual changes in their functional imaging.¹⁹ Athletes who received a greater number of head impacts during a given time period demonstrated reduced oxygenated blood flow to the brain, indicating that subconcussive impacts may play a role in lower activation levels within the frontal lobe of the brain.^{3,30} This is a significant finding since the frontal lobe is associated with working memory.^{26,31,32} Lastly, cumulative head impacts have been shown to

have a significant relationship to Diffusion Tensor Imaging.⁴ It measures the movement of water molecules along white matter and this movement is seen to be faster parallel to white matter than perpendicular.³³⁻³⁷ The difference between parallel and perpendicular movement is the basis of Diffusion Tensor Imaging.³³ White matter is unique in that it is myelinated which increases the transmission of neural signals through white matter.³³ Diffusion Tensor Imaging is able to track subtle changes in white matter over relatively small amounts of time within a single subject.^{4,38} Decreases in diffusivity may indicate a diseased state in the brain. Changes in diffusivity are associated with changes in cognitive function.⁴ This is related to concussion and can be seen in athletes without a clinical diagnosis of concussion.⁴ On the contrary, further studies have also shown no significant impairments in visual memory, verbal memory, reaction time, and BESS scores after the course of one season.^{20,30,39} Therefore, the true effect of subconcussive impacts remains unknown to investigators and further research is needed to better understand the topic. Studying the potential detrimental effects of subconcussive impacts warrants further investigation within other body systems.

Traditionally, an assessment battery comprised of postural stability, cognition, self-reported symptoms, and neuropsychological testing is highly sensitive in the assessment of concussion.⁴⁰ Investigators have also used some of these measures in an attempt to assess changes associated with subconcussive head impacts.^{2,19-22,25,26} The Balance Error Scoring System (BESS) is widely used by clinicians for the assessment of postural stability and it is popular due to its low cost and practicality.⁴¹ Furthermore, the National Collegiate Athletic Association (NCAA) and the National Athletic Training Association state that all participating athletes should undergo a motor control measurement (i.e. balance assessment) during preseason baseline measures.⁴² The BESS test is comprised of a total of 6 static stances performed on both

a firm surface and foam surface. Any deviations from these stances are counted as “errors” and totaled at the end of the test for an overall score. However, the BESS test has many limitations. It is only seen to be moderately reliable in concussion assessment and has a practice effect associated with serial administration.^{20,43} When using the BESS test for pre- and post-season measures, Division I athletes that sustain subconcussive impacts showed a significant decrease in scores.²⁰ This implies an improvement in postural control over the course of one season.⁴⁴ In Division I football players, the same result of increased postural stability has been observed from pre- to post-season.²² A linear regression also revealed that the number of head impacts, the cumulative magnitude of linear accelerations, and the number of previous concussions sustained were predictors of improved postural stability.³⁹ This further builds the idea of a practice or learning effect with multiple administrations within a relatively short period of time. However, it is still one of the most widely used clinical balance assessment tools.⁴³

Force platforms are commonly reported in the literature to be more sensitive to detect changes in postural stability.^{10,12,17,22,45,46} Linear measures of postural stability determine the amount of sway magnitude during a time series. These measures, such as root mean squared center of pressure displacement and velocity, have shown remaining deficits at the time of return to play.⁴⁷ The “typical” window is seen in previous research utilizing the BESS test and Sensory Organization Test scores.^{12,46,48,49} In these studies, baseline values were reached within a 3-4 day period following a concussion when deficits may still be present.

Nonlinear measures of postural stability have been used to determine abnormal postural control post-concussion. Unlike linear measures, nonlinear dynamics measures the repeatability of a signal within a time series.⁵⁰ The repeatability of a time series or how constrained the signal exposes the adaptability of the motor system.⁵¹ Nonlinear measures are given in unitless numbers

from 0 to 2.⁵² Zero values represent a complete regularity and a 2 indicates complete randomness.⁵² Thus, a lower value is considered more regular and a higher value is considered to be more irregular. Granata and England stated that variability refers to a motor system's ability to perform reliably in a variety of environments.^{53,54}

Approximate Entropy (ApEn), is one reported nonlinear measure used to investigate postural control post-concussion.^{45,50-52} The ApEn algorithm is a highly iterative process that analyzes the recurrent nature of short sequences of data points considered incrementally throughout a time series.⁵⁴ ApEn have been able to detect postural instability from center of pressure data where linear measures had not.⁵⁵ Since non-linear measures quantify the regularity of the system output, ApEn may provide potential clues to how a system is organized.⁵⁶ The theory is that a system with a limited number of interconnections between separate components may present as more regular. Thus, it can be suggested that an impaired system, that has fewer degrees of freedom, will show a more normalized regularity and have less adaptive capacity to the surrounding environment.⁵⁴ However, ApEn has not been used in the assessment of subconcussive impacts and may warrant investigation.⁵⁷

Gait analysis has been used to assess changes in postural stability. Investigators have utilized systems, such as the Gaitrite (CIR Systems, Sparta, NJ), to measure the many parameters of gait.^{9,10,13,14,16,58-60} Measures of gait can be taken during single task (ST) or dual task (DT) scenarios. ST is simply walking at a self-selected "normal" pace. Concussed athletes have greater mediolateral (ML) sway compared to non-concussed athletes.⁶¹ These individuals had to conservatively adjust their whole body center of mass motion to maintain dynamic stability when walking during ST.⁶² DT can involve cognitive tasks or even physical obstacles the participant must react to while walking. Typically, individuals (both athletes and non-athletes) exhibit a

slower gait velocity during DT conditions.⁶¹ However, concussed athletes demonstrate greater ML sway and sway velocity up to 28 days following the initial injury compared to non-concussed.⁶¹⁻⁶⁴ During obstacle avoidance tasks, concussed participants had more contact with obstacles when compared to controls.⁶⁵ This means their spatial attention was impaired leading to more contact with obstacles. A sample of college-aged individuals showed impairments 4 weeks after suffering a concussion.⁶⁶ These lingering deficits may be absent in ST gait conditions, indicating that DT may be more sensitive in detecting lasting and minute changes in gait.⁶⁷ Overall, concussed individuals tend to adopt a more conservative gait strategy in the sagittal plane.⁶⁷⁻⁶⁹ Gait analysis has not been conducted to explore the effects of subconcussive impacts in contact athletes.

Several tools are available to help better understand what occurs to the head during an impact. The Head Impact Telemetry System (HITS) (Simbex, Lebanon, NH) consists of an encoder with six uniaxial accelerometers. The encoders are inserted into Riddell Revolution and Riddell Speed model helmets and are able measure the kinematics of helmet impacts. Specifically, it measures linear acceleration, rotational acceleration, and impact location. Each accelerometer continuously samples impacts throughout play during practices and competitions. This allows researchers to have measureable data for each impact a player takes. As far as concussive impacts, there is still a debate on the theoretical threshold. The mean NFL concussion was seen at a linear acceleration of 98 g when concussive impacts were reconstructed in a laboratory setting.⁷⁰ However, the mean college concussive impact was measured at 102 g.⁷¹ The proposed low-end threshold, as of now, is 60-80 g.⁷⁰⁻⁷² In the collegiate setting, the average head impact measures at 21-22 g and can suffer as many as 1400 impacts in a season.⁷³⁻⁷⁵ Typically, an athlete sees between about 950 and 1350 head impacts a season, but this number is largely

dependent on the style of offense or defense, play status, and position.^{71,74,76-78} Head Injury Criterion (HIC) has also been used in previous literature for the correlation of concussion incidence.⁷⁹ HIC was developed by the National Highway Traffic Safety Administration in 1972.⁸⁰ It is used to measure the potential for head injury associated with global linear resultant accelerations.⁸⁰ It is still currently in use by the Federal Motor Vehicle Safety Standard 208.⁸¹

Additionally, HITS has previously been used in the assessment of subconcussive impacts in collegiate athletes.^{4,19,22,25,26} Variables used in these studies include: total number of impacts, maximal linear and rotational acceleration, summation of linear acceleration, summation of rotational acceleration, number of impacts above a 90g threshold, number of impacts to the top of the head, number of previous concussions, and number of years played.^{25,39} Results of these studies indicate that individuals that have participated in football longer show decreased postural stability and those with greater peak linear forces show memory deficits.^{22,25}

A traditional assessment of concussion consists of symptoms, neurocognitive testing, and postural stability testing.⁴² No traditional assessment is available for the effects of subconcussive blows. However, it is possible that more traditionally used tools for concussion assessment may be used. Thus, the primary purpose of this study was to examine the effects of subconcussive impacts on postural stability in division I football athletes. We hypothesize that all participants will show declines in postural stability following a single fall season. We also hypothesized that there will be no significant differences between Division I football athletes that have suffered subconcussive impacts and a group that had not from pre- to post-season for ApEn in both the ML and AP directions, as well as step length (SL) and step rate (SR). The secondary purpose was to predict deficits in postural stability based on cumulative linear acceleration, cumulative rotational acceleration, total number of impacts, and HIC. We hypothesize that the total number

of impacts and cumulative linear acceleration will predict significant changes in postural stability.

Methods

Participants

Experimental: Forty Division I Football Bowl Subdivision football players (SUBC) were recruited for this investigation. After initial recruitment, 16 athletes were unwilling to continue to wear encoders, six athletes were unwilling to return for postseason testing, one athlete had a lower extremity injury at the time of postseason testing, and two athletes sustained concussions during the season. Fifteen participated in this study for the entirety of a single fall season (age = 20.40 ± 1.12 years, height = 183.90 ± 7.61 cm, mass = 100.32 ± 22.08 kg, concussion history = 0.60 ± 0.83). The sample included a variety of positions. There were a total of 6 offensive linemen, 3 wide receivers, 1 running back, 1 defensive line, 2 linebackers, and 2 defensive backs. The inclusion criterion for the experimental participants was members of the football team with HITS encoders installed in their helmets. The exclusion criteria for this study was a previous history of concussion three months prior to the baseline testing date, a lower extremity injury at the times of a testing session, a season ending injury in the fall season, or having sustained a concussion during the duration of the fall season. Any participants were excluded if they had self-reported vestibular, visual, or balance deficits due to neurologic or other disorders as determined by their previous medical history in a questionnaire at the time of testing. (Appendix D)

Control: Thirteen control (CONT) participants (2 male, 11 female) were recruited from a single collegiate cheerleading team (age = 19.85 ± 1.21 year, height = 161.19 ± 9.31 cm, mass = 58.30 ± 10.51 kg, concussion history = 0.80 ± 0.99). These athletes were selected based on their minimal risk for multiple subconcussive head impacts. The exclusion criteria for this study was a previous history of concussion three months prior to the baseline testing date, a lower extremity

injury at the times of a testing session, a season ending injury in the fall season, or having sustained a concussion during the duration of the fall season. Any participants were excluded if they had self-reported vestibular, visual, or balance deficits due to neurologic or other disorders as determined by their previous medical history in a questionnaire at the time of testing.

(Appendix D)

All participants from both groups gave written informed consent before participating in the study that was approved by the university's Institutional Review Board. Athletes that participated in sports outside the umbrella of the NCAA were compensated for each testing session they completed.

Instrumentation

BESS is an inexpensive clinical tool used to assess postural stability following concussion.^{12,46,49,82} The test consists of 3 stances: double leg, single leg, and tandem stance. Each stance was completed on a hardwood floor and then repeated on a medium density foam Airex pad for 20 s each. Finnoff et al. in 2009 measured an intrarater reliability of 0.5 to 0.88, an interrater reliability of 0.44 to 0.83, validity of 0.57, an intrarater minimum detectable change of 7.4, and an interrater minimal detectable change of 9.3.⁴³ BESS has been shown to have moderate to high criterion-related validity in the assessment of postural stability post-concussion.³¹ For this investigation, the primary investigator scored the number of errors, or deviations from the original position. A score of 1 point was assigned for each error committed and summed for a total score. Each stance has a maximum score of 10 points and multiple errors occurring simultaneously are scored as a single error.

The HITS (Simbex, Lebanon, NH) was developed by Simbex in association with Virginia Tech between 2000 and 2003. It has been used in several settings to collect impact data from

games and practices in near real-time at different American football athletic levels. There are several components of the system including the MX Encoders (sensor sets imbedded in the helmets), and the Sideline Response System (includes the computer system and receiver antenna). MX Encoders have a total of 6 separate accelerometers that measure linear and rotational accelerations of the skull based on proprietary calculations for the skull's center of mass. The HIT system's accuracy has been validated through headform and dummy testing in previous investigations.⁸³ However, there was a report that demonstrated the previous HITS validation studies used methods that did not simulate the typical helmet fitting norms used by athletes by exceeding athlete comfort levels.⁸¹ This same investigation showed that impacts might be inaccurately low or high with larger inaccuracies seen with impacts occurring to the facemask and may not be accurate enough to properly predict head biomechanics in helmet impacts.⁸¹ Thus, if used as a concussion diagnostic tool, the instances of false negatives and false positives could be erroneously high.

Encoders were installed in each participant's helmets prior to the start of the fall season. Each MX Encoder recorded linear and rotational accelerations from head impacts sustained during all practices and games. The data was wirelessly transmitted to the Sideline Response System (SRS) onto a laptop computer. The data was recorded and viewable in real time if an impact exceeded a linear acceleration of 10 g. A total of 40 ms of data from each impact was recorded; 8ms before the impact and 32 ms after. The sensors had a range of 140-185 m. If the sensors were out of the transmission area, up to 100 impacts were stored within an onboard memory system and sent to the SRS when the player returned within receiver range. The encoders were designed to comply with the National Operating Committee on Standards for

Athletic Equipment standards for football helmets. Total number of impacts, cumulative linear accelerations, cumulative rotational acceleration, and HIC were measured by HITS and recorded.

In this study, a 40 x 60 cm strain gauge force platforms (1000 Hz, AMTI model OR-6, Watertown, MA) were utilized to measure ApEn. The force platforms were set flush into the floor, level with the ground. Each participant performed both single leg and double leg barefoot static balance trials with their eyes open. Single leg trials were performed 3 times for 20 s on the right foot and then 3 times for 20 s on the left foot. The participant stood on one leg with the other leg in 90° of knee flexion and in a neutral hip position. Their hands were relaxed at their side. One double leg trial was performed with feet together (medial malleolus to medial malleolus), arms relaxed at their side, for 2 min. During this stance a verbal update at each 30 s time interval was given. Data was collected and processed through Vicon Nexus 1.8.5. (Vicon, Denver, CO).

The Gaitrite walkway (CIR Systems, Sparta, NJ) is a pressure mat system that automates measuring temporospatial gait parameters via an electronic walkway. As the individual walks across the mat, the system continuously scans to detect objects on the walkway. The Gaitrite system has shown good test-retest reliability. Validity ranging 0.84 to 0.90 and a test-retest reliability from 0.72 to 0.94 has been recorded in previous research.⁸⁴⁻⁸⁶ For this study, the participants performed 10, single task (ST) barefoot walking trials at a self-selected “normal speed”. Each participant then performed 5 more walking dual task (DT) trials while performing a changing, additional cognitive task.

Procedures

Prior to the season, a HITS encoder was installed in each football participant's helmet. Each helmet was tested prior to use to assure the encoders were functioning properly.

For preseason testing, participants were tested within 2 weeks prior to the start of the fall season. Each participant filled out a graded symptom checklist and a health history questionnaire (Appendix D). BESS was performed and scored by the lead investigator. Gait analysis was performed barefoot along an 8 m walkway. Participants completed 10 trials at a self-selected, ST, "normal" walking pace along the Gaitrite walkway. They were instructed when to initiate walking by a researcher at the start of each trial with the verbal cue, "Looking straight ahead, go." Each participant performed 5 more trials, each of them under a separate DT condition. These 5 conditions are: reciting the months of the year in reverse order starting with May, reciting the days of the week backwards starting with Friday, serial sevens starting at 100, spelling a 5 letter word (house) backwards, and consecutive additions. SL and SR were measured and recorded for each trial under both conditions. Each participant then performed a total of 3 single-leg trials on each leg and 1 double-leg trial (DL). A single leg trial was performed for 20 s. Each participant was instructed to stand on one leg with the other knee flexed to 90°. A DL trial was done for 2 min and the participant was instructed to have their feet together. They were instructed to stand as still as possible for the duration of each trial. For each stance, ApEn in the AP and ML directions was calculated from the recorded raw center of pressure coordinates.

Intervention: The fall season was considered the intervention. SUBC had HITS installed in their helmets and participated normally throughout the season. Impact data was recorded for each athlete exposure for practices and games. No collection or analysis of head impact exposure was completed with CONT.

Post-season: The participants were tested within 2 weeks of the final day of the fall football season. The same process for pre-season testing was repeated using the same instruments and testing protocol.

Data Analysis

This was a prospective longitudinal study. The independent variables for this study were the fall season (Time) and student athletes (Groups). The dependent variables for head impact measures were total number of impacts, cumulative linear acceleration (g), cumulative rotational acceleration (rad/s^2), and HIC. Dependent variables for static postural stability were BESS total score; single leg stances on the right foot in the AP (RAP) and ML (RML) directions; the left foot for AP (LAP) and ML (LML) directions; and double leg in the AP (DLAP) and ML (DLML) directions. For gait, SL was calculated under a ST (SLST) and DT (SLDT) condition. A participant's SR was calculated under a ST (SRST) and DT (SRDT) condition via the Gaitrite system for all testing trials and conditions.

Statistical Analysis

SPSS version 21 (SPSS Inc., Armonk, NY) was used to run statistical analyses. Eight mixed model ANOVAs were run for time (pre-test, post-test) and group (SUBC, CONT) for all measures of postural stability. Parameter estimates were calculated for each. Four separate multiple linear regression analyses were used with change scores (absolute value of preseason minus postseason) for total BESS score, SL, SR, and ApEn for total number of impacts, cumulative linear acceleration, cumulative rotational acceleration, and HIC to predict the post-season dependent variable outcomes. An alpha level of 0.05 was set a priori.

RESULTS

Head Impact Telemetry System

Participants in the SUBC group took an average of 622.27 ± 515.46 impacts during the season. Cumulative and mean linear accelerations were $18,042.95 \pm 15,811.89$ g and 26.90 ± 3.11 g, respectively. Cumulative and mean rotational accelerations were $61,1298.13 \pm 49,9510.34$ rad/s² and 949.18 ± 197.00 rad/s². Lastly, cumulative HIC was $13,670.61 \pm 13,945.79$. (Appendix C, Table 2)

Balance Error Scoring System

BESS at preseason for SUBC and CONT was 16.47 ± 7.39 errors and 9.44 ± 5.96 errors, respectively. BESS at postseason for SUBC and CONT was 14.20 ± 7.60 errors and 9.31 ± 4.332 errors, respectively. (Appendix C, Table 3)

There was no significant interaction for BESS between time and group [$F(1,29) = 0.84$, $p = 0.37$, $\eta = 0.03$]. Therefore there was no difference between SUBC and CONT from preseason to postseason. There was, however, a significant difference between groups [$F(1,29) = 9.01$, $p < 0.01$, $\eta = .24$]. SUBC and CONT were significantly different at preseason ($p < 0.01$, $\eta = 0.23$) as well as postseason ($p = 0.35$, $\eta = 0.15$).

Step Length

SLST at preseason for SUBC and CONT was 68.13 ± 6.15 cm and 64.95 ± 4.39 cm, respectively. SLST at postseason for SUBC and CONT was 68.51 ± 6.44 cm and 65.62 ± 5.15 cm, respectively. (Appendix C, Table 4)

There was no significant difference for SLST between time and group [$F(1,29) = 0.18$, $p = 0.67$, $\eta < 0.01$]. Therefore, there was no difference between SUBC and CONT from preseason

to postseason. There was also no significant difference between SUBC and CONT at both preseason ($p = 0.11$, $\eta = 0.09$) and postseason ($p = 0.18$, $\eta = 0.06$).

SLDT at preseason for SUBC and CONT was 62.95 ± 7.76 cm and 61.22 ± 5.28 cm, respectively. SLDT at postseason for SUBC and CONT was 65.42 ± 8.52 cm and 62.05 ± 5.45 cm, respectively. (Appendix C, Table 4)

There was no significant interaction for SLDT between time and group [$F(1,29) = 3.80$, $p = 0.06$, $\eta = 0.12$]. Therefore, there was no difference between SUBC and CONT from preseason to postseason. There was no significant difference between SUBC and CONT at both preseason ($p = 0.47$, $\eta = 0.02$) and postseason ($p = 0.20$, $\eta = 0.06$) tests. However, there was a significant increase from preseason to postseason ($p < 0.01$).

Step Rate

SRST at preseason for SUBC and CONT was 111.91 ± 9.88 steps \cdot min⁻¹ and 119.28 ± 7.87 steps \cdot min⁻¹, respectively. SRST at postseason for SUBC and CONT was 111.30 ± 8.39 steps \cdot min⁻¹ and 121.05 ± 9.05 steps \cdot min⁻¹, respectively. (Appendix C, Table 4)

There was no significant interaction for SRST between time and group [$F(1,29) = 2.59$, $p = 0.12$, $\eta = 0.08$]. Therefore, there was no difference between SUBC and CONT from preseason to postseason. SUBC showed a significantly slower SRST at both preseason ($p = 0.03$, $\eta = 0.16$) and postseason ($p < 0.01$, $\eta = 0.25$).

SRDT at preseason for SUBC and CONT was 101.36 ± 10.99 steps \cdot min⁻¹ and 106.42 ± 8.20 steps \cdot min⁻¹, respectively. SRDT at postseason for SUBC and CONT was 105.67 ± 7.51 steps \cdot min⁻¹ and 111.39 ± 8.11 steps \cdot min⁻¹, respectively. (Appendix C, Table 4)

There was no significant interaction for SRDT between time and group [$F(1,29) = 0.08$, $p = 0.78$, $\eta < 0.01$]. Therefore, there was no difference between SUBC and CONT from

preseason to postseason. There was no significant difference between SUBC and CONT at preseason ($p = 0.16$, $\eta = 0.07$). However, SUBC showed a slower SRDT at postseason ($p = 0.05$, $\eta = 0.13$). There was a significant decrease in SUBC from preseason to postseason ($p < 0.01$).

Static Stance Right Leg

RAP at preseason for SUBC and CONT was 0.81 ± 0.12 and 0.74 ± 0.12 , respectively.

RAP at postseason for SUBC and CONT was 0.79 ± 0.11 and 0.77 ± 0.11 , respectively.

(Appendix C, Table 5)

There was no significant interaction for RAP between time and group [$F(1,29) = 0.55$, $p = 0.47$, $\eta = 0.02$]. Thus, there was no difference between SUBC and CONT from preseason to postseason. There was no significant difference between SUBC and CONT at preseason ($p = 0.19$, $\eta = 0.07$) and postseason ($p = 0.56$, $\eta = 0.01$). There was no significant change for SUBC and CONT over time [$F(1,29) = 0.09$, $p = 0.76$, $\eta < 0.01$].

RML at preseason for SUBC and CONT was 0.92 ± 0.06 and 0.93 ± 0.06 , respectively.

RML at postseason for SUBC and CONT was 0.91 ± 0.07 and 0.94 ± 0.08 , respectively.

(Appendix C, Table 5)

There was no significant interaction for RML between time and group [$F(1,29) = 0.30$, $p = 0.59$, $\eta = 0.01$]. Thus, there was no difference between SUBC and CONT from preseason to postseason. There was no significant difference between SUBC and CONT at preseason ($p = 0.62$, $\eta < 0.01$) and postseason ($p = 0.30$, $\eta = 0.04$). There was no significant change for SUBC and CONT over time [$F(1,29) < 0.01$, $p = .95$, $\eta < 0.01$].

Static Stance Left Leg

LAP at preseason for SUBC and CONT was 0.77 ± 0.11 and 0.70 ± 0.11 , respectively.

LAP at postseason for SUBC and CONT was 0.79 ± 0.14 and 0.81 ± 0.10 , respectively.

(Appendix C, Table 5)

There was a significant interaction for LAP between time and group [$F(1,29) = 4.38$, $p = 0.04$, $\eta = 0.14$]. Thus, there was a significant increase for SUBC and CONT from preseason to postseason. There was no significant difference between SUBC and CONT at preseason ($p = 0.13$, $\eta = 0.09$) and postseason ($p = 0.72$, $\eta < 0.01$). There was a significant increase for SUBC and CONT over time [$F(1,29) = 11.81$, $p < 0.01$, $\eta = 0.31$].

LML at preseason for SUBC and CONT was 0.92 ± 0.09 and 0.90 ± 0.07 , respectively.

LML at postseason for SUBC and CONT was 0.90 ± 0.05 and 0.92 ± 0.06 , respectively.

(Appendix C, Table 5)

There was no significant interaction for LML between time and group [$F(1,29) = 2.50$, $p = 0.13$, $\eta = 0.09$]. Thus, there was no difference between SUBC and CONT from preseason to postseason. There was no significant difference between SUBC and CONT at preseason ($p = 0.62$, $\eta = 0.01$) and postseason ($p = 0.32$, $\eta = 0.04$). There was no significant change for SUBC and CONT over time [$F(1,29) < 0.01$, $p = 0.96$, $\eta < 0.01$].

Static Stance Double Leg

DLAP at preseason for SUBC and CONT was 0.56 ± 0.14 and 0.55 ± 0.06 , respectively.

DLAP at postseason for SUBC and CONT was 0.52 ± 0.13 and 0.53 ± 0.11 , respectively.

(Appendix C, Table 5)

There was no significant interaction for DLAP between time and group [$F(1,29) = 0.04$, $p = 0.84$, $\eta < 0.01$]. Thus, there was no difference between SUBC and CONT from preseason to postseason. There was no significant difference between SUBC and CONT at preseason ($p =$

0.86, $\eta < 0.01$) and postseason ($p = 0.95$, $\eta < 0.01$). There was no significant change for SUBC and CONT over time [$F(1,29) = 1.38$, $p = .25$, $\eta = 0.05$].

DLML at preseason for SUBC and CONT was 0.55 ± 0.14 and 0.62 ± 0.08 , respectively.

DLML at postseason for SUBC and CONT was 0.59 ± 0.09 and 0.69 ± 0.09 , respectively.

(Appendix C, Table 5)

There was a significant interaction for DLML between time and group [$F(1,29) = 0.28$, $p = 0.60$, $\eta = 0.01$]. There was no significant difference between SUBC and CONT at preseason ($p = 0.08$, $\eta = 0.11$). However, SUBC showed a significant increase at postseason ($p < 0.01$, $\eta = 0.26$).

Linear Regression

Change scores were calculated to assess the difference in scores from preseason to postseason for each variable. Total number of impacts ($p = 0.63$), cumulative linear acceleration ($p = 0.90$), cumulative rotational acceleration ($p = 0.47$), and HIC ($p = 0.26$) did not significantly predict change in total BESS scores.

Number of impacts ($p = 0.84$), cumulative linear acceleration ($p = 0.95$), cumulative rotational acceleration ($p = 0.68$), and HIC ($p = 0.63$) did not significantly predict change in SLST. Number of impacts ($p = 0.84$), cumulative linear acceleration ($p = 0.95$), cumulative rotational acceleration ($p = 0.68$), and HIC ($p = 0.63$) did not significantly predict change in SLST. Number of impacts ($p = 0.40$), cumulative linear acceleration ($p = 0.89$), cumulative rotational acceleration ($p = 0.31$), and HIC ($p = 0.97$) did not significantly predict change in SLDT. Number of impacts ($p = 0.40$), cumulative linear acceleration ($p = 0.60$), cumulative rotational acceleration ($p = 0.48$), and HIC ($p = 0.80$) did not significantly predict change in SRST. Number of impacts ($p = 0.70$), cumulative linear acceleration ($p = .64$), cumulative

rotational acceleration ($p = 0.96$), and HIC ($p = 0.93$) did not significantly predict change in SRDT.

Number of impacts ($p = 0.97$), cumulative linear acceleration ($p = 0.97$), cumulative rotational acceleration ($p = 0.90$), and HIC ($p = 0.91$) did not significantly predict change in LAP. Number and impacts ($p = 0.86$), cumulative linear acceleration ($p = 0.60$), cumulative rotational acceleration ($p = 0.76$), and HIC ($p = 0.46$) did not significantly predict change in LML. Number of impacts ($p = 0.68$), cumulative linear acceleration ($p = 0.75$), cumulative rotational acceleration ($p = 0.70$), and HIC ($p = 0.84$) did not significantly predict change in RAP. Number of impacts ($p = 0.62$), cumulative linear acceleration ($p = 0.84$), cumulative rotational acceleration ($p = 0.58$), and HIC ($p = 0.78$) did not significantly predict change in RML. Number of impacts ($p = 0.52$), cumulative linear acceleration ($p = 0.10$), cumulative rotational acceleration ($p = 0.38$), and HIC ($p = 0.10$) did not significantly predict change in DLAP. Number of impacts ($p = 0.76$), cumulative linear acceleration ($p = 0.75$), cumulative rotational acceleration ($p = 0.44$), and HIC ($p = 0.76$) did not significantly predict change in DLML.

DISCUSSION

The primary purpose of this study was to examine the effects of subconcussive impacts on postural stability in division I football athletes. It was hypothesized that both the SUBC and CONT group would show declines of postural stability over the course of a single fall season. Overall, we observed no significant deficits over the course of a single athletic season due to head impacts. We did see a significant increase in static stances, but concluded that these were not clinically significant due to lack of prediction with the use of a linear regression analysis.

Balance Error Scoring System

We hypothesized that BESS scores for both SUBC and CONT would increase over the course of the fall season. Gysland et al. in 2012 reported a mean of 23.22 errors prior to the season and 17.39 errors following the season.²² McCrea et al. in 2003 reported a mean of 11.89 to 12.73 at baseline.⁴⁹ At preseason, we observed mean total errors for SUBC and CONT of 16.47 ± 7.39 and 9.44 ± 5.96 , respectively, and 12.84 ± 7.48 overall, which falls within the range of previously reported means.^{22,49} We observed no significant difference between testing sessions for both groups. This contradicts previous research that has reported a practice effect with serial administration of the BESS test with improved scores over the course of a season.^{20,22} However, within both testing sessions, we saw a large range of scores. Outliers exceeding 30 total points existed at preseason and postseason measures. This is another limitation of the administration of this test.

In previous investigations, athletes have shown a significant increase in BESS scores from pre to post measures over the course of a single athletic season. This is said to be associated with a practice effect with multiple administrations of the test.^{20,22} However, in this investigation

there was no significant difference within both groups over the course of a single season. These findings disagree with the existing literature.

We saw a significantly higher total error scores in the SUBC group compared to the CONT at both preseason and postseason testing. Previous research has shown an average BESS total score of 9.1 ± 5.39 in gymnastics population.⁸⁷ This is in agreement with the results of this investigation in our CONT group. Zimmer et al. in 2013 showed an average BESS total score of 22.22 ± 8.16 in football athletes. This result is higher than in this investigation, but similar. Therefore, the difference within groups of our investigation was statistically significant, but does not appear to be clinically significant. On average, clinicians should expect to see an average BESS score that is higher in football athletes when compared to cheerleaders due to the nature and training of their sport.

Gait

It was hypothesized that SUBC would demonstrate a shorter SL and slower SR following the season, which would be indicative of a more conservative gait strategy. SL and SR were not to be found a variable previously researched in subconcussive literature. The normative values can be seen in Table 4. Our results showed that both groups significantly increased SLDT, which is not supportive by our hypothesis. However, SRST in SUBC was significantly lower than CONT at postseason testing.

Measures of SL are not found in previous investigations of subconcussive impacts. Parker et al. measured stride length, which is the length of two steps, and showed a significantly longer stride in ST condition compared to DT in concussed and non-concussed individuals.^{13,14} They also showed that concussed athletes demonstrated more mediolateral sway when comparing ST and DT conditions. Athletes also demonstrated more mediolateral center of mass

sway when compared to a non-concussed population.^{13,14} In a young, healthy population, Sekiya et al. showed that males and females demonstrate a mean SL of 0.76 m and 0.69 m, respectively at a self-selected pace. A second experiment within the same investigation showed a SL of 0.71 m in a female population.⁸⁸ Judge et al. showed that healthy, young adults have a SL of 0.74 m. This study shows similar results to previous research regarding SL in a healthy population.⁸⁹ Though we hypothesized that SUBC would demonstrate a more conservative gait, our results indicate that subconcussive impacts do not impair SL.

Similar to SL, SR has not been seen in previous literature in the assessment of subconcussive impacts. However, previous research measuring SR in healthy populations does exist. In the same investigation looking at SL, Sekiya et al. showed that males and females have a mean SR of 108.4 and 106.4 steps \cdot min⁻¹, respectively. In their second experiment, females demonstrated a SR of 116.2 steps \cdot min⁻¹. Again, no statistical differences were seen between males and females.⁸⁸ Judge et al showed similar results in that healthy, young adults demonstrate a SR of 110 steps \cdot min⁻¹.⁸⁹ Our results show that the SUBC group has a significantly lower SR when compared to CONT at both preseason and postseason measures in a ST condition. However, there was no significant increase or decrease over time. This suggests that football athletes have a slower natural gait when compared to an average cheerleader. Under a DT condition, SUBC showed a significantly lower SR than CONT at postseason measures. There was no significant change over time. Therefore, again, this demonstrates that football athletes have a slower average gait when compared to cheerleaders.

This investigation only examined a few simple measures of gait. Though we used a mixed sample of males and females, previous literature supports the notion that there are no major differences between young, healthy populations across genders. There was no

demonstration of impaired gait over the course of a single season. These findings support the notion that subconcussive impacts do not induce gait impairment. However, future studies in this field should take other variables used in a concussed population into consideration. Future investigations may look at gait initiation and gait termination as demonstrated by Buckley et al., mediolateral sway as seen by Parker et al., and gait velocity also used by Parker et al.^{8,13-15}

Static Stance

It was hypothesized that both groups would demonstrate lower measures of ApEn over the course of a single season, demonstrating less randomness, which is indicative of a more impaired postural stability. Results of this study suggest that subconcussive impacts do not demonstrate detriments in static stance assessments of postural stability. We did see a significant increase for LAP in both groups over the course of the season with no significant difference between groups at both time points. We also saw a significant increase in ApEn for DLML in SUBC from preseason to postseason. However, these increases are not seen to be clinically significant due to their small effect size.

As mentioned earlier, BESS has been used in several studies to assess static postural stability in athletes that suffer subconcussive impacts. Though this is true, no literature exists that measures ApEn in athletes that sustain subconcussive impacts. Gysland et al. demonstrated that there was no significant difference between preseason and postseason measures when using the composite equilibrium balance change score of the Sensory Organization Test in football athletes over the course of a single season. However, Cavanaugh et al. in 2007 showed that healthy adults demonstrated a more irregular ApEn measure under a DT condition that was not detected by root mean squared displacement and equilibrium score.⁴⁵ In 2005, Cavanaugh et al showed concussed athletes that have normal postural stability measures (equilibrium score) still showed changes in

center of pressure oscillations.⁵² This indicates that nonlinear algorithms may reveal more subtle changes than traditional linear measures.^{45,52} In the 2007 study, Cavanaugh et al. observed ApEn of 0.474-0.810 and 0.810-1.020 in the AP and ML directions, respectively.⁴⁵ Our results show an increase in LAP from preseason to postseason in both SUBC and CONT. We also saw that DLAP significantly increased between SUBC and CONT at postseason. These results are not seen to be clinically significant, again, due to their small effect size. Therefore, head impacts do not affect static measures of postural stability over the course of a single athletic season.

A few possibilities exist to help explain our results. Firstly, increases in static postural stability over the course of a season may be due to a training effect. Athletes partake in extremely sport-specific training over several months. Depending on the sport or position, this could result in an increase of postural stability.

Secondly, the increase over the course of the season may be due to a practice effect of the testing protocol. For each testing session, participants performed three static stances on their right foot, and then performed three on their left. This “warm-up” on the right foot could possibly lead to a practice effect on the left foot.

Linear Regression

The secondary purpose was to predict deficits in postural stability based on cumulative linear acceleration, cumulative rotational acceleration, total number of impacts, and HIC.

Gysland et al. used the Sensory Organization Test to measure potential deficits over the course of a single season.²² The results of the linear regression analysis showed that the number of years playing football significantly predicted a lower overall composite equilibrium balance change score from preseason to postseason. More years played showed a lower, or worse, score.²² We hypothesized that cumulative linear acceleration and total number of impacts would predict

declines seen in postural stability following a single fall season. Normative values for HITS data can be seen in Table 2. In previous literature, mean number of impacts suffered ranged from 469 to around 1200 over the entire season. Mean summation of linear acceleration and rotational acceleration was 11,963 g and 836,796 rads/s², respectively.^{22,25}

In this investigation, we observed that total number of impacts, cumulative linear acceleration, cumulative rotational acceleration, and HIC did not significantly predict outcome measures of static postural stability and gait. Therefore, the potential deficits in gait and static stance are not determined by biomechanical measures of head impacts.

Late-Life Implications

This investigation showed no significant impairment of postural stability over the course of a single athletic season due to chronic exposure to head impacts. However, There is a growing area of research that suggests there may be long-term deficits associated with them. Both athletes and non-athletes have shown late-life complications that have been associated with head impacts and multiple concussions.^{23,90-95}

Multiple concussions have been associated with many conditions later in life. In former NFL players, the prevalence of clinical depression was seen to be a function of previous head injury.⁹³ Those with three or more concussions were 3 times more likely to have a clinical diagnosis of depression. These same athletes also reported having greater limitations during day-to-day activities, more alcohol related problems, and were more likely to be separated and divorced from their significant other.⁹³ Another similar study observed that former NFL players were also susceptible to mild cognitive impairment at an earlier age.²³ Athletes with 3 or more concussions were 5 times more likely to suffer from mild cognitive impairment.²³ They were also 3 times more likely to suffer from memory problems.²³ Similarly, military personnel are also

susceptible to brain injury. Soldiers with a history of traumatic brain injury were more likely to suffer from depression, post-traumatic stress disorder, and lingering signs and symptoms of traumatic brain injury.⁹¹ These risks increased with the number of traumatic brain injuries suffered. More disturbingly, those with a more lifetime brain injuries showed a higher suicide risk.⁹¹

Other investigations have also shown changes within the brain that are associated with memory and cognition issues.^{90,92} Broglio et al demonstrated that young adults that reported at least one mild traumatic brain injury within 3 years of their investigation showed deficits in the neuroelectric system. These changes occurred in the absence of functional declines.⁹⁰ De Beaumont et al. showed that athletes that had suffered multiple concussions had long lasting P3 amplitude suppression.⁹² This P3 amplitude is associated with memory issues.^{96,97}

Lastly, the controversial topic of chronic traumatic encephalopathy continues to emerge. Chronic traumatic encephalopathy is a progressive neurodegeneration within the brain that is associated with memory disturbances, behavioral changes, personality changes, Parkinsonism, and abnormalities in speech and gait. It is proposed to be caused by repetitive brain trauma.⁹⁴ Though some still consider concussion a mild and transient injury, research in this area shows there may be more severe and devastating consequences of repetitive brain trauma that may not manifest until later in life.⁹⁵

Conclusion

The results of this investigation indicate that subconcussive impacts may not impair postural stability pertaining to measures of gait in a ST and DT condition over the course of a single season. Along with gait, static measures were also showed no impairment across one athletic season. SLDT, LAP, and DLAP measures showed improved stability, though it is not

seen to be clinically significant. This could be explained by one or more of the following: training effect of an athletic season, practice effect of tests, and submaximal effort during baseline testing.

Our regression analysis further supports the notion that subconcussive impacts do not have a significant effect on changes in postural stability. However, this investigation utilized measures that were not seen in previous research. Thus, there is a need for further investigation into these same measures of postural stability, as well as others, to measure potential deficits brought on by chronic exposure to subconcussive head impacts.

Though this investigation demonstrates no deficits due to head impacts over a short period of time, there is growing concern regarding the effects that head impacts may have in the long term. The growing body of literature regarding late-life issues arising from brain injury is alarming. Repetitive brain trauma may lead to clinical depression, mild cognitive impairment, neural degeneration, risk of suicide, and other mental and emotional disorders. Care should be taken when competing in collision sports, more so when a previous history of concussion exists.

REFERENCES

1. Breedlove EL, Robinson M, Talavage TM, et al. Biomechanical correlates of symptomatic and asymptomatic neurophysiological impairment in high school football. *J Biomech.* 2012;45(7):1265-1272.
2. Davenport EM, Whitlow CT, Urban JE, et al. Abnormal white matter integrity related to head impact exposure in a season of high school varsity football. *Journal of neurotrauma.* 2014;31(19):1617-1624.
3. Johnson B, Neuberger T, Gay M, Hallett M, Slobounov S. Effects of subconcussive head trauma on the default mode network of the brain. *Journal of neurotrauma.* 2014;31(23):1907-1913.
4. Volberding J, Melvin D. Changes in ImPACT and Graded Symptom Checklist Scores During a Division I Football Season. *Athletic Training & Sports Health Care.* 2014;6(4):6.
5. Breedlove EL, Robinson M, Talavage TM, et al. Biomechanical correlates of symptomatic and asymptomatic neurophysiological impairment in high school football. *Journal of biomechanics.* 2012;45(7):1265-1272.
6. Burk JM, Munkasy BA, Joyner AB, Buckley TA. Balance error scoring system performance changes after a competitive athletic season. *Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine.* 2013;23(4):312-317.
7. Dashnaw ML, Petraglia AL, Bailes JE. An overview of the basic science of concussion and subconcussion: where we are and where we are going. *Neurosurgical focus.* 2012;33(6):E5: 1-9.
8. Gysland SM, Mihalik JP, Register-Mihalik JK, Trulock SC, Shields EW, Guskiewicz KM. The relationship between subconcussive impacts and concussion history on clinical measures of neurologic function in collegiate football players. *Annals of biomedical engineering.* 2012;40(1):14-22.
9. Guskiewicz KM, Marshall SW, Bailes J, et al. Association between recurrent concussion and late-life cognitive impairment in retired professional football players. *Neurosurgery.* 2005;57(4):719-726; discussion 719-726.
10. Guskiewicz KM, Marshall SW, Bailes J, et al. Recurrent concussion and risk of depression in retired professional football players. *Med Sci Sports Exerc.* 2007;39(6):903-909.
11. McAllister TW, Flashman LA, Maerlender A, et al. Cognitive effects of one season of head impacts in a cohort of collegiate contact sport athletes. *Neurology.* 2012;78(22):1777-1784.
12. Buxton RB. *Introduction to functional magnetic resonance imaging : principles and techniques.* 2nd ed. Cambridge ; New York: Cambridge University Press; 2009.
13. Codington-Lacerte C. *Functional magnetic resonance imaging.* Salem Press; 2013.
14. Smith K. Brain imaging: fMRI 2.0. *Nature.* 2012;484(7392):24-26.
15. Talavage TM, Nauman EA, Breedlove EL, et al. Functionally-Detected Cognitive Impairment in High School Football Players Without Clinically-Diagnosed Concussion. *J Neurotrauma.* 2013.

16. Talavage TM, Nauman EA, Breedlove EL, et al. Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion. *Journal of neurotrauma*. 2014;31(4):327-338.
17. Farrell JA, Landman BA, Jones CK, et al. Effects of signal-to-noise ratio on the accuracy and reproducibility of diffusion tensor imaging-derived fractional anisotropy, mean diffusivity, and principal eigenvector measurements at 1.5 T. *Journal of magnetic resonance imaging : JMRI*. 2007;26(3):756-767.
18. Gysland SM, Mihalik JP, Register-Mihalik JK, Trulock SC, Shields EW, Guskiewicz KM. The relationship between subconcussive impacts and concussion history on clinical measures of neurologic function in collegiate football players. *Ann Biomed Eng*. 2012;40(1):14-22.
19. Broglio SP, Macciocchi SN, Ferrara MS. Sensitivity of the concussion assessment battery. *Neurosurgery*. 2007;60(6):1050-1057; discussion 1057-1058.
20. Bailes JE, Petraglia AL, Omalu BI, Nauman E, Talavage T. Role of subconcussion in repetitive mild traumatic brain injury. *Journal of neurosurgery*. 2013;119(5):1235-1245.
21. Finnoff JT, Peterson VJ, Hollman JH, Smith J. Intrarater and interrater reliability of the Balance Error Scoring System (BESS). *Pm R*. 2009;1(1):50-54.
22. Finnoff JT, Peterson VJ, Hollman JH, Smith J. Intrarater and interrater reliability of the Balance Error Scoring System (BESS). *PM & R : the journal of injury, function, and rehabilitation*. 2009;1(1):50-54.
23. Burk JM, Munkasy BA, Joyner AB, Buckley TA. Balance error scoring system performance changes after a competitive athletic season. *Clin J Sport Med*. 2013;23(4):312-317.
24. Catena RD, van Donkelaar P, Chou LS. Altered balance control following concussion is better detected with an attention test during gait. *Gait & posture*. 2007;25(3):406-411.
25. Cavanaugh JT, Mercer VS, Stergiou N. Approximate entropy detects the effect of a secondary cognitive task on postural control in healthy young adults: a methodological report. *Journal of neuroengineering and rehabilitation*. 2007;4:42.
26. Guskiewicz KM, Ross SE, Marshall SW. Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes. *Journal of athletic training*. 2001;36(3):263-273.
27. Powers KC, Kalmar JM, Cinelli ME. Recovery of static stability following a concussion. *Gait & posture*. 2014;39(1):611-614.
28. Riemann BL, Guskiewicz KM. Effects of mild head injury on postural stability as measured through clinical balance testing. *Journal of athletic training*. 2000;35(1):19-25.
29. Powers KC, Kalmar JM, Cinelli ME. Recovery of static stability following a concussion. *Gait Posture*. 2013.
30. Guskiewicz KM, Ross SE, Marshall SW. Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes. *J Athl Train*. 2001;36(3):263-273.
31. Riemann BL, Guskiewicz KM. Effects of mild head injury on postural stability as measured through clinical balance testing. *J Athl Train*. 2000;35(1):19-25.
32. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *Jama*. 2003;290(19):2556-2563.

33. Guskiewicz KM, Riemann BL, Perrin DH, Nashner LM. Alternative approaches to the assessment of mild head injury in athletes. *Med Sci Sports Exerc.* 1997;29(7 Suppl):S213-221.
34. Granata KP, England SA. Reply to the Letter to the Editor. *Gait & posture.* 2007;26:329-330.
35. Stergiou N, Decker LM. Human movement variability, nonlinear dynamics, and pathology: is there a connection? *Human movement science.* 2011;30(5):869-888.
36. Cavanaugh JT, Mercer VS, Stergiou N. Approximate entropy detects the effect of a secondary cognitive task on postural control in healthy young adults: a methodological report. *J Neuroeng Rehabil.* 2007;4:42.
37. Pincus SM, Goldberger AL. Physiological time-series analysis: what does regularity quantify? *The American journal of physiology.* 1994(4):1643.
38. Broglio SP, Eckner JT, Paulson HL, Kutcher JS. Cognitive decline and aging: the role of concussive and subconcussive impacts. *Exerc Sport Sci Rev.* 2012;40(3):138-144.
39. Catena RD, van Donkelaar P, Chou LS. Cognitive task effects on gait stability following concussion. *Experimental brain research.* 2007;176(1):23-31.
40. Catena RD, van Donkelaar P, Chou LS. Different gait tasks distinguish immediate vs. long-term effects of concussion on balance control. *J Neuroeng Rehabil.* 2009;6:25.
41. Martini DN, Sabin MJ, DePesa SA, et al. The chronic effects of concussion on gait. *Arch Phys Med Rehabil.* 2011;92(4):585-589.
42. Parker TM, Osternig LR, van Donkelaar P, Chou LS. Balance control during gait in athletes and non-athletes following concussion. *Med Eng Phys.* 2008;30(8):959-967.
43. Parker TM, Osternig LR, Lee HJ, Donkelaar P, Chou LS. The effect of divided attention on gait stability following concussion. *Clin Biomech (Bristol, Avon).* 2005;20(4):389-395.
44. Catena RD, van Donkelaar P, Chou LS. Altered balance control following concussion is better detected with an attention test during gait. *Gait Posture.* 2007;25(3):406-411.
45. Parker TM, Osternig LR, van Donkelaar P, Chou LS. Recovery of cognitive and dynamic motor function following concussion. *Br J Sports Med.* 2007;41(12):868-873; discussion 873.
46. Catena RD, van Donkelaar P, Halterman CI, Chou LS. Spatial orientation of attention and obstacle avoidance following concussion. *Experimental brain research.* 2009;194(1):67-77.
47. Parker TM, Osternig LR, P VAND, Chou LS. Gait stability following concussion. *Med Sci Sports Exerc.* 2006;38(6):1032-1040.
48. Pellman EJ, Viano DC, Tucker AM, Casson IR, Waeckerle JF. Concussion in professional football: reconstruction of game impacts and injuries. *Neurosurgery.* 2003;53(4):799-812; discussion 812-794.
49. Guskiewicz KM, Mihalik JP, Shankar V, et al. Measurement of head impacts in collegiate football players: relationship between head impact biomechanics and acute clinical outcome after concussion. *Neurosurgery.* 2007;61(6):1244-1252; discussion 1252-1243.
50. Hugenholtz H, Richard MT. Return to athletic competition following concussion. *Can Med Assoc J.* 1982;127(9):827-829.

51. Brolinson PG, Manoogian S, McNeely D, Goforth M, Greenwald R, Duma S. Analysis of linear head accelerations from collegiate football impacts. *Curr Sports Med Rep*. 2006;5(1):23-28.
52. Crisco JJ, Fiore R, Beckwith JG, et al. Frequency and location of head impact exposures in individual collegiate football players. *J Athl Train*. 2010;45(6):549-559.
53. Mihalik JP, Bell DR, Marshall SW, Guskiewicz KM. Measurement of head impacts in collegiate football players: an investigation of positional and event-type differences. *Neurosurgery*. 2007;61(6):1229-1235; discussion 1235.
54. Bailes JE, Petraglia AL, Omalu BI, Nauman E, Talavage T. Role of subconcussion in repetitive mild traumatic brain injury. *J Neurosurg*. 2013;119(5):1235-1245.
55. Guskiewicz KM, Mihalik JP. Biomechanics of sport concussion: quest for the elusive injury threshold. *Exerc Sport Sci Rev*. 2011;39(1):4-11.
56. Schnebel B, Gwin JT, Anderson S, Gatlin R. In vivo study of head impacts in football: a comparison of National Collegiate Athletic Association Division I versus high school impacts. *Neurosurgery*. 2007;60(3):490-495; discussion 495-496.
57. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *Jama*. 2003;290(19):2556-2563.
58. Register-Mihalik JK, Mihalik JP, Guskiewicz KM. Balance deficits after sports-related concussion in individuals reporting posttraumatic headache. *Neurosurgery*. 2008;63(1):76-80; discussion 80-72.
59. Beckwith JG, Greenwald RM, Chu JJ. Measuring head kinematics in football: correlation between the head impact telemetry system and Hybrid III headform. *Annals of biomedical engineering*. 2012;40(1):237-248.
60. Jadischke R, Viano DC, Dau N, King AI, McCarthy J. On the accuracy of the Head Impact Telemetry (HIT) System used in football helmets. *Journal of biomechanics*. 2013;46(13):2310-2315.
61. Clark RA, Bower KJ, Mentiplay BF, Paterson K, Pua YH. Concurrent validity of the Microsoft Kinect for assessment of spatiotemporal gait variables. *J Biomech*. 2013;46(15):2722-2725.
62. Greene BR, Foran TG, McGrath D, Doheny EP, Burns A, Caulfield B. A comparison of algorithms for body-worn sensor-based spatiotemporal gait parameters to the GAITRite electronic walkway. *J Appl Biomech*. 2012;28(3):349-355.
63. Kuys SS, Brauer SG, Ada L. Test-retest reliability of the GAITRite system in people with stroke undergoing rehabilitation. *Disabil Rehabil*. 2011;33(19-20):1848-1853.
64. Bressel E, Yonker JC, Kras J, Heath EM. Comparison of static and dynamic balance in female collegiate soccer, basketball, and gymnastics athletes. *Journal of athletic training*. 2007;42(1):42-46.
65. Parker TM, Osternig LR, P VAND, Chou LS. Gait stability following concussion. *Medicine and science in sports and exercise*. 2006;38(6):1032-1040.
66. Parker TM, Osternig LR, Lee HJ, Donkelaar P, Chou LS. The effect of divided attention on gait stability following concussion. *Clinical biomechanics*. 2005;20(4):389-395.
67. Sekiya N, Nagasaki H, Ito H, Furuna T. Optimal walking in terms of variability in step length. *The Journal of orthopaedic and sports physical therapy*. 1997;26(5):266-272.

68. Judge JO, Davis RB, 3rd, Ounpuu S. Step length reductions in advanced age: the role of ankle and hip kinetics. *The journals of gerontology. Series A, Biological sciences and medical sciences*. 1996;51(6):M303-312.
69. Parker TM, Osternig LR, van Donkelaar P, Chou LS. Recovery of cognitive and dynamic motor function following concussion. *British journal of sports medicine*. 2007;41(12):868-873; discussion 873.
70. Buckley TA, Munkasy BA, Tapia-Lovler TG, Wikstrom EA. Altered gait termination strategies following a concussion. *Gait & posture*. 2013;38(3):549-551.
71. Cavanaugh JT, Guskiewicz KM, Stergiou N. A nonlinear dynamic approach for evaluating postural control: new directions for the management of sport-related cerebral concussion. *Sports medicine*. 2005;35(11):935-950.
72. Guskiewicz KM, Marshall SW, Bailes J, et al. Recurrent concussion and risk of depression in retired professional football players. *Medicine and science in sports and exercise*. 2007;39(6):903-909.
73. Bryan CJ, Clemans TA. Repetitive traumatic brain injury, psychological symptoms, and suicide risk in a clinical sample of deployed military personnel. *JAMA psychiatry*. 2013;70(7):686-691.
74. Broglio SP, Pontifex MB, O'Connor P, Hillman CH. The persistent effects of concussion on neuroelectric indices of attention. *Journal of neurotrauma*. 2009;26(9):1463-1470.
75. De Beaumont L, Brisson B, Lassonde M, Jolicoeur P. Long-term electrophysiological changes in athletes with a history of multiple concussions. *Brain injury : [BI]*. 2007;21(6):631-644.
76. Donchin E, Coles MG. Is the P300 component a manifestation of context updating? *Behavioral and Brain Sciences*. 1988;11(3):357-427.
77. Johnson R, Jr., Donchin E. On how P300 amplitude varies with the utility of the eliciting stimuli. *Electroencephalography and clinical neurophysiology*. 1978;44(4):424-437.
78. McKee AC, Cantu RC, Nowinski CJ, et al. Chronic traumatic encephalopathy in athletes: progressive tauopathy after repetitive head injury. *Journal of neuropathology and experimental neurology*. 2009;68(7):709-735.
79. McKee AC, Stern RA, Nowinski CJ, et al. The spectrum of disease in chronic traumatic encephalopathy. *Brain : a journal of neurology*. 2013;136(Pt 1):43-64.
80. Chrisman SP, Schiff MA, Rivara FP. Physician concussion knowledge and the effect of mailing the CDC's "Heads Up" toolkit. *Clin Pediatr (Phila)*. 2011;50(11):1031-1039.
81. Lannsjö M, Backheden M, Johansson U, Af Geijerstam JL, Borg J. Does head CT scan pathology predict outcome after mild traumatic brain injury? *Eur J Neurol*. 2013;20(1):124-129.
82. Kutcher JS, McCrory P, Davis G, Pfitz A, Meeuwisse WH, Broglio SP. What evidence exists for new strategies or technologies in the diagnosis of sports concussion and assessment of recovery? *Br J Sports Med*. 2013;47(5):299-303.
83. Llewellyn T, Burdette GT, Joyner AB, Buckley TA. Concussion Reporting Rates at the Conclusion of an Intercollegiate Athletic Career. *Clin J Sport Med*. 2013.
84. Valovich McLeod TC, Schwartz C, Bay RC. Sport-related concussion misunderstandings among youth coaches. *Clin J Sport Med*. 2007;17(2):140-142.
85. Cantu RC. Second-impact syndrome. *Clin Sports Med*. 1998;17(1):37-44.
86. McCrory P, Berkovic S. The History of Clinical and Pathophysiological Concepts and Misconceptions. *Neurology*. 2008;57:2283-2289.

87. Giza CC, Hovda DA. The Neurometabolic Cascade of Concussion. *J Athl Train*. 2001;36(3):228-235.
88. McCrea M, Guskiewicz K, Randolph C, et al. Effects of a symptom-free waiting period on clinical outcome and risk of reinjury after sport-related concussion. *Neurosurgery*. 2009;65(5):876-882; discussion 882-873.
89. Guskiewicz KM, Weaver NL, Padua DA, Garrett WE, Jr. Epidemiology of concussion in collegiate and high school football players. *Am J Sports Med*. 2000;28(5):643-650.
90. Register-Mihalik JK, Guskiewicz KM, McLeod TC, Linnan LA, Mueller FO, Marshall SW. Knowledge, attitude, and concussion-reporting behaviors among high school athletes: a preliminary study. *J Athl Train*. 2013;48(5):645-653.
91. Saunders EA, Burdette GT, Metzler JN, Joyner AB, Buckley TA. Knowledge of Coaching Education Students Regarding Sport-Related Concussions. *Athletic Training & Sports Health Care: The Journal for the Practicing Clinician*. 2013;5(1):11-19.
92. Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. *J Head Trauma Rehabil*. 2006;21(5):375-378.
93. Shankar PR, Fields SK, Collins CL, Dick RW, Comstock RD. Epidemiology of high school and collegiate football injuries in the United States, 2005-2006. *Am J Sports Med*. 2007;35(8):1295-1303.
94. Gessel LM, Fields SK, Collins CL, Dick RW, Comstock RD. Concussions among United States high school and collegiate athletes. *J Athl Train*. 2007;42(4):495-503.
95. Powell JW, Barber-Foss KD. Traumatic brain injury in high school athletes. *Jama*. 1999;282(10):958-963.
96. Marar M, McIlvain NM, Fields SK, Comstock RD. Epidemiology of concussions among United States high school athletes in 20 sports. *Am J Sports Med*. 2012;40(4):747-755.
97. Covassin T, Swanik CB, Sachs ML. Sex Differences and the Incidence of Concussions Among Collegiate Athletes. *J Athl Train*. 2003;38(3):238-244.
98. Maddocks DL, Dicker GD, Saling MM. The assessment of orientation following concussion in athletes. *Clin J Sport Med*. 1995;5(1):32-35.
99. Shores EA, Marosszeky JE, Sandanam J, Batchelor J. Preliminary validation of a clinical scale for measuring the duration of post-traumatic amnesia. *Med J Aust*. 1986;144(11):569-572.
100. Yarnell PR, Lynch S. The 'ding': amnesic states in football trauma. *Neurology*. 1973;23(2):196-197.
101. Delaney JS, Lacroix VJ, Leclerc S, Johnston KM. Concussions among university football and soccer players. *Clin J Sport Med*. 2002;12(6):331-338.
102. McCrea M, Kelly JP, Randolph C, Cisler R, Berger L. Immediate neurocognitive effects of concussion. *Neurosurgery*. 2002;50(5):1032-1040; discussion 1040-1032.
103. McCrea M, Kelly JP, Kluge J, Ackley B, Randolph C. Standardized assessment of concussion in football players. *Neurology*. 1997;48(3):586-588.
104. McCrea M, Kelly JP, Randolph C, et al. Standardized assessment of concussion (SAC): on-site mental status evaluation of the athlete. *J Head Trauma Rehabil*. 1998;13(2):27-35.
105. Valovich McLeod TC, Perrin DH, Guskiewicz KM, Shultz SJ, Diamond R, Gansneder BM. Serial administration of clinical concussion assessments and learning effects in healthy young athletes. *Clin J Sport Med*. 2004;14(5):287-295.

106. Bell DR, Guskiewicz KM, Clark MA, Padua DA. Systematic review of the balance error scoring system. *Sports health*. 2011;3(3):287-295.
107. Register-Mihalik JK, Guskiewicz KM, Mihalik JP, Schmidt JD, Kerr ZY, McCrea MA. Reliable change, sensitivity, and specificity of a multidimensional concussion assessment battery: implications for caution in clinical practice. *J Head Trauma Rehabil*. 2013;28(4):274-283.
108. Guskiewicz KM, Bruce SL, Cantu RC, et al. National Athletic Trainers' Association Position Statement: Management of Sport-Related Concussion. *J Athl Train*. 2004;39(3):280-297.
109. McCrea M, Guskiewicz K, Randolph C, et al. Incidence, clinical course, and predictors of prolonged recovery time following sport-related concussion in high school and college athletes. *J Int Neuropsychol Soc*. 2013;19(1):22-33.
110. McCrea M, Barr WB, Guskiewicz K, et al. Standard regression-based methods for measuring recovery after sport-related concussion. *J Int Neuropsychol Soc*. 2005;11(1):58-69.
111. Meehan WP, 3rd, Mannix RC, Straccioli A, Elbin RJ, Collins MW. Symptom severity predicts prolonged recovery after sport-related concussion, but age and amnesia do not. *J Pediatr*. 2013;163(3):721-725.
112. Lau BC, Collins MW, Lovell MR. Cutoff scores in neurocognitive testing and symptom clusters that predict protracted recovery from concussions in high school athletes. *Neurosurgery*. 2012;70(2):371-379; discussion 379.
113. Ferrara MS, McCrea M, Peterson CL, Guskiewicz KM. A Survey of Practice Patterns in Concussion Assessment and Management. *J Athl Train*. 2001;36(2):145-149.
114. Moser RS, Glatts C, Schatz P. Efficacy of immediate and delayed cognitive and physical rest for treatment of sports-related concussion. *J Pediatr*. 2012;161(5):922-926.
115. Gibson S, Nigrovic LE, O'Brien M, Meehan WP, 3rd. The effect of recommending cognitive rest on recovery from sport-related concussion. *Brain Inj*. 2013;27(7-8):839-842.
116. Majerske CW, Mihalik JP, Ren D, et al. Concussion in sports: postconcussive activity levels, symptoms, and neurocognitive performance. *J Athl Train*. 2008;43(3):265-274.
117. Guskiewicz KM, McCrea M, Marshall SW, et al. Cumulative effects associated with recurrent concussion in collegiate football players: the NCAA Concussion Study. *Jama*. 2003;290(19):2549-2555.
118. Slobounov S, Slobounov E, Sebastianelli W, Cao C, Newell K. Differential rate of recovery in athletes after first and second concussion episodes. *Neurosurgery*. 2007;61(2):338-344; discussion 344.
119. Zemper ED. Two-year prospective study of relative risk of a second cerebral concussion. *Am J Phys Med Rehabil*. 2003;82(9):653-659.
120. Eisenberg MA, Andrea J, Meehan W, Mannix R. Time interval between concussions and symptom duration. *Pediatrics*. 2013;132(1):8-17.
121. Iverson GL, Brooks BL, Lovell MR, Collins MW. No cumulative effects for one or two previous concussions. *Br J Sports Med*. 2006;40(1):72-75.
122. Collins MW, Lovell MR, Iverson GL, Cantu RC, Maroon JC, Field M. Cumulative effects of concussion in high school athletes. *Neurosurgery*. 2002;51(5):1175-1179; discussion 1180-1171.

123. Pellman EJ, Viano DC, Tucker AM, Casson IR. Concussion in professional football: location and direction of helmet impacts-Part 2. *Neurosurgery*. 2003;53(6):1328-1340; discussion 1340-1321.
124. Daniel RW, Rowson S, Duma SM. Head impact exposure in youth football. *Ann Biomed Eng*. 2012;40(4):976-981.
125. Broglio SP, Sosnoff JJ, Shin S, He X, Alcaraz C, Zimmerman J. Head impacts during high school football: a biomechanical assessment. *J Athl Train*. 2009;44(4):342-349.
126. Aukerman DF, Aukerman MM, Browning D. Medical coverage of high school athletics in North Carolina. *South Med J*. 2006;99(2):132-136.
127. McCaffrey MA, Mihalik JP, Crowell DH, Shields EW, Guskiewicz KM. Measurement of head impacts in collegiate football players: clinical measures of concussion after high- and low-magnitude impacts. *Neurosurgery*. 2007;61(6):1236-1243; discussion 1243.
128. Resch J, Driscoll A, McCaffrey N, et al. ImPact test-retest reliability: reliably unreliable? *J Athl Train*. 2013;48(4):506-511.

APPENDIX A

Delimitations

This study was delimited to NCAA Division I male intercollegiate football student athletes from a single university over a single fall season. The study was also delimited to non-contact student athletes from the same university over a single fall season.

Limitations

As with any study, a few limitations exist. First, a maximum of 40 participants for each group were able to be included. This is due to only having 40 HITS encoders that readily available for installation in helmets. Second, only male athletes were included in the test group since there are only males on the football team. Lastly, we were unable to control for loss of participation time due to injury, illness, disciplinary action, or lack of compliance.

Assumptions

We assumed that participants gave maximal effort in all parameters of the testing protocol. We assumed that football athletes did not alter their style of play due to the sensors. This could be attempting to take minimal impacts, or trying to register the highest impact. We also assumed that all of the equipment used was correct, reliable, and calibrated correctly.

Hypotheses

HO1: There will not be a significant decline in ApEn for single leg stances and double leg stances from preseason to postseason.

HA1: SUBC and CONT will demonstrate a significant decline in ApEn for single leg stances and double leg stances from preseason to postseason.

HO2: There will be no significant difference between SUBC and CONT in ApEn for single leg stances and double leg stances from preseason to postseason.

HA2: SUBC and CONT will show a significant difference in ApEn for single leg stances and double leg stances from preseason to postseason.

HO3: There will be no significant difference between SUBC and CONT for SL and SR from preseason to postseason.

HA3: SUBC will demonstrate a significantly lower SL and slower SR from preseason to postseason.

HO4: There will be no significant difference between SUBC and CONT for SL and SR at preseason and postseason.

HA4: SUBC will demonstrate a significantly lower SL and a slower SR at postseason when compared to CONT.

HO5: Cumulative linear acceleration and total number of impacts will show no relationship to declines in postural stability following a single fall season.

HA5: Cumulative linear acceleration and total number of impacts will predict declines in ApEn, SL, and SR for SUBC.

APPENDIX B

Literature review

History

Concussions have long been misunderstood and therefore are feared by many. It is also the source of non-confidence for many Allied Health Care providers.⁹⁸ This may all be due to the fact that concussions are an “invisible” injury. Clinicians are unable to see concussions whether it be a physical examination or through imaging such as Computed Tomography (CT) or Magnetic Resonance Imaging (MRI).^{99,100} This leaves athletic trainers, physicians, and the like to rely on their injury recognition skills as well as trusting their athletes are being truthful. Though clinicians are trained to recognize concussions, athletes still lie about symptoms and hide their injury. Not only that, but a lack of education can also lead to lack of recognition by the athletes, coaches, and parents.^{101,102} These scenarios are dangerous and could lead to second impact syndrome. This is a condition that is potentially lethal.¹⁰³

The study of head injury started more than 3000 years ago. It was first used in its modern sense by Rhazes in 900 A.D. and defined as, “Abnormal transient physiologic state without gross brain lesions.”¹⁰⁴ Medieval medicine was the start of further understanding of the signs and symptoms of concussion. Coiter (1573) described acute symptoms as “faltering in the speech, impairing of the memory, dullness of understanding and a weak judgment.” The “learned Doctor Read,” mentioned a number of defined events that almost perfectly match what is known today: “(1) a ringing of the ears after the wound is received, (2) falling after the blow, (3) swooning for a time, (4) slumbering after the wound is received, (6) dazzling of the eyes, (7) a giddiness which

passes rapidly.”¹⁰⁴ These descriptions can all be associated with now commonly known signs and symptoms of concussion as well as cranial nerve impairment.

There were also important observations made in the 17th, 18th, and 19th centuries. With the invention of the microscope and the Age of Enlightenment many individuals looked further into pathophysiologic understanding of concussion. Medical minds such as Cooper described patients with concussion as developing their symptoms days to weeks after the initial loss of consciousness (LOC). This shows the shift to using “concussion” as a descriptor of only symptoms. Kirkland concluded that the extravasted blood that is found during autopsy occurs later and that LOC from trauma (that he termed concussion) is not associated with pathologic change.¹⁰⁴ This view of concussion still stands today. Current understanding focuses on the fact that clinical features of concussion primarily reflect a functional neuronal disturbance.¹⁰⁴

Pathophysiology

Though concussions are not seen with imaging, there are changes that occur at the cellular level that account for the neurological deficits that arise post injury. Giza and Hovda referred to this as the neurometabolic cascade of concussion.¹⁰⁵ In the study they induced cerebral concussion in rats to examine the effects and showed there is a very complex cascade of ionic, metabolic, and physiologic events.¹⁰⁵

Immediately following injury there is a release of excitatory neurotransmitters, such as glutamate, that leads to further neuronal depolarization as well as an efflux of potassium (K^+) and an influx of calcium (Na^+). The sodium-potassium (Na^+-K^+) pumps work overtime in an attempt to restore ionic levels and neuronal membrane potential. The Na^+-K^+ pumps require adenosine triphosphate (ATP) to continue to function properly. This sends the cells into a state of

hypermetabolism to keep up with energy demands. Since there is diminished cerebral blood flow at this time, glucose availability is decreased which triggers a cellular energy crisis. The hypermetabolic state leads to the accumulation of lactate as a byproduct. This, paired with persistent increases in Ca^{+} , leads to impaired mitochondrial oxidative metabolism. Since oxidative metabolism is impaired, ATP production is also decreased. Therefore, the lack of cerebral blood flow, increased metabolic activity, impaired oxidative metabolism, and build up of lactate are all contributing to the cellular energy crisis. Apoptosis is initiated to stop this dysfunctional action potential from continuing down the neuronal chain. This “cellular suicide” is initiated by calpain proteins as a means of self-preservation.¹⁰⁵

Important things to note within this process are time lines for certain events. After the initial period of hyperglycolysis, cerebral glucose use is diminished by 24 hours postinjury and remains low for 5 to 10 days. Positron emission tomography (PET) in humans shows similar decreases in global cerebral glucose metabolism that may last 2-4 weeks post TBI.¹⁰⁵ These numbers are very consistent with research showing symptom duration lasting between 7 and 10 days.^{106,107} A return to participation of less than seven days has also been seen to increase the risk of reinjury.¹⁰⁶

Epidemiology

Concussion is one of the biggest topics of the sports world today. The notion in the American society is that the prevalence of concussion is very high. It is common thought that this increased incidence is due to the fact that the motivation to participate in collision sports has led to bigger, faster, and stronger athletes. These improvements are believed to also increase the

velocity of collisions and severity of head injuries in football.¹⁰⁸ This common conclusion may be due to the sensationalized high-profile cases of concussion reported by the media.

Another misconception among the general population includes signs and symptoms (S/S) of concussion.^{109,110} LOC is one of the most commonly recognized signs, however, it is common thought that you must have LOC to have received the injury.¹⁰² Though LOC and PTA frequently occur with concussion, they are not mandatory to be diagnosed. When these two signs are absent, clinicians turn toward self-reported symptoms to aid their evaluation.

The Centers of Disease Control and Prevention (CDC) approximates that 1.6 to 3.8 million sport-related concussions occur annually in the United States. However, the leading causes of concussions are falls and motor vehicle crashes, not collision sports.¹¹¹ Shankar et al estimated that 517,726 football-related injuries occurred at the high school level in the United States during 2005-2006. Of those injuries, only 11.5% were of the head/face. 96.1% of the head/face injuries were concussion. This only accounts for 1.5-3.5% of all sport-related concussions. Contrary to popular belief, that could either mean most of the concussions that occur happen outside of high school football, or that the estimates are too high.¹¹²

When comparing football across the different skill and school levels, there is a significant difference. Some literature suggests the percentage of injured athletes decreases as the level of play increases, meaning high school has the highest followed by division III, then division II, and finally division I.¹⁰⁸ These increased numbers are thought to be caused by a number of things including: increased exposure (athletes playing offense and defense), quality and condition of protective equipment, and skill level of the players.¹⁰⁸ However some findings disagree and suggest that concussions have been more prevalent in college than at the high school level.

Gessel et al showed that concussions are approximately 1.86 times more prevalent at the collegiate level.¹¹³ Although football accounts for the majority, sport related concussions occur in other sports. For girl's sports, soccer has the highest rate at 6.2% of mTBI cases among high school athletes and 4.3% of all reported injuries. Boy's wrestling and demonstrated the second highest rate for male sports and accounted for 10.5% of mTBI cases and 4.4% of all reported injuries.¹¹⁴

Though each sport and level is different, there are some similarities. Player to player contact was the main cause of concussive injury, followed by player contact with playing surface.¹¹⁵ Literature consistently supports higher percentage of concussions occur during competition than in practice.^{112,113,115} Also, females tend to have a higher rate of concussion than males in gender comparable sports.^{113,115,116} Several explanations exist for this difference that include: females may be more honest, have weaker neck musculature, and biomechanical differences. These biomechanical differences are due to smaller head to ball ratios as well as less total mass of the head and neck. It has been demonstrated that an increased head mass results in decreased linear acceleration of the head. Since females tend to have smaller heads and necks, the acceleration forces are greater.^{113,115}

Though football receives the most heat about concussions in sports, most concussions are seen outside of athletics. Not only that, but they are also prevalent in most other sports rather than just football. Girl's soccer has the second most incidences of concussion, which bring ups the issue of gender differences. Females have an increased risk of concussion compared to males that can be attributed to weaker neck musculature, head to ball mass ratios, and other biomechanical differences. Care should be taken in all sports, not just high-risk sports, to help reduce and prevent concussion from occurring.

Assessment

In the assessment of concussion, it is crucial to add objective information for health care providers to an injury that does not show on diagnostic imaging. Simple and practical tests exist to assess symptoms, postural stability, and cognition. Neuropsychological testing is also becoming more accessible to institutions to aid in the assessment of multiple impairments following MTBI.

LOC and PTA have been associated with concussion. Since concussion can occur without LOC, a sensitive assessment of PTA is needed. Traditionally, assessment of PTA has been based on asking questions that are related to time, person and place.¹¹⁷ Typical questions may include: “How old are you?” “Where are you?”; and “What year is it?” These have been shown to be sensitive in the assessment of PTA of head injury caused by motor vehicle accidents.^{117,118} However, simple orientation questioning may not be sensitive in the cases of sport related mild traumatic brain injury (MTBI). It has been suggested that questions pertaining to recent events related to the game in progress may be more appropriate.^{117,119} Maddocks et al developed a series of memory recall questions and tested them in professional Australian Rules Football club. Appropriately, these have since been termed the “Maddocks Questions.” They showed that memory recall questions were more sensitive when compared to the standard orientations questions when assessing a potential concussion.¹¹⁷

A Graded Symptom Checklist (GSC) is a self-report list of concussion symptoms. The athlete ranks the severity of each symptom on a 0-6 Likert scale, 0 meaning no symptom and 6 being severe. Immediately post injury, a rise of 15-26 points is usually seen.¹⁰⁷ Common symptoms associated with concussion include: headache (HA), dizziness, difficulty

concentrating, confusion, and blurred vision. HA was consistently seen as the most commonly reported symptom.^{108,117,120}

Standardized Assessment of Concussion (SAC) is series of questions and memory recall tests that was developed to provide clinicians with a more objective and standardized immediate assessment of mild traumatic brain injury (MTBI).¹²¹ Scores range from 0 to 30 and higher scores on the exam are considered better. It has been shown in research to be a reliable method of measuring mental status and neurologic abnormalities within minutes of MTBI incidence among athletes.^{122,123} The typical athlete will see a decrease of 3 to 4 points following a concussion.¹²¹ There is, however, a slight increase in scores that reached statistical significance from baseline scores to post injury scores in a study conducted by McCrea et al.¹²¹ This increase could be attributed to a learning effect associated with the assessment. Repetition of the immediate memory words as well as the injured athlete knowing that these words will be asked again later in the test could be explanations for this increase. Recently, different word lists and number series have been added to the assessment to better control for this effect.

The Balance Error Scoring System (BESS) is widely used to assess changes in balance post-concussion. It was developed to provide clinicians with an inexpensive and practical tool to assess postural stability.^{41,124} Subjects are instructed to place their hands on their hips, close their eyes, and stand in 3 different positions (double leg stance, single leg stance, and tandem stance) on two different surfaces (firm and foam). Each stance is held for 20 seconds and an examiner scores the subject's postural stability using an objective list of specific errors. Each error is worth one point and the maximum score for each position is 10, with a maximum total score of 60.⁴¹ Immediately post-concussion, an increase of 7 errors is typically seen.⁴¹ The question of whether the BESS is a reliable assessment tool has frequently been asked. Findings suggest that when

scored by the same individual, the single-leg firm-stance, tandem firm-stance, and double-leg foam stance positions may be valid measures of postural stability ($ICC > 0.75$). The remaining stances and the total BESS score may not be valid. Finnoff et al also concluded that only single-leg firm stance may be valid when errors are counted by different scorers.⁴¹ These ICCs were lower than previously reported.^{124,125} It is suggested that reliability can be ensured by using one scorer and averaging 3 scores per stance for a final score.¹²⁶ Interrater and intrarater minimal detectable change (MDC) has also been assessed. An intrarater MDC of 7.3 points and an interrater MDC of 9.4 points is typical.⁴¹ The MDC signifies the number of points needed to show a change in the athlete's postural stability. Therefore, a 7.3 point change within the same rater and a 9.4 point change between raters is needed to show a change in postural stability. One significant issue seen with the BESS tests is the occurrence of athletes scoring below their baseline scores after sustaining a concussion. This supports the existence of a practice effect.⁴⁴

Neuropsychological testing has shifted from pencil and paper exams with a neuropsychologist to computer based testing due to ease of access. Two of the more common computerized exams are Immediate Post-concussion Assessment and Cognitive Test (ImPACT) and Automated Neuropsychological Assessment Metrics (ANAM). Both exams include multiple modules that test areas such as reaction time, motor speed, and memory. ANAM has 5 testing modules: simple reaction time, math processing, procedural reaction time, code substitution, Sternberg procedure, and match to sample. The sensitivity of each separate module has been shown to be low. However, the sensitivity of the entire battery is much higher.¹²⁷ ImPACT also has 5 composite scores: verbal memory, visual memory, visual motor speed, reaction time, and impulse control. It was shown by Broglio et al that the sensitivity of ImPACT alone was only

62.5%. However, this percentage increased to 79.2% with the addition of a graded symptom inventory. A pencil and paper assessment battery was only seen to be 43.5% sensitive.⁴⁰

Though individual tests may be administered in the assessment of concussion, their stand-alone sensitivities are poor. The current literature recommends and supports the use of a multi-faceted approach. An entire battery of tests have been shown to be 89-96% sensitive in the assessment of concussion.⁴⁰ Testing should include measures of neurocognitive function, postural control, and self-reported symptoms.^{40,127,128}

Gait analysis has been used to assess changes in postural stability. Investigators utilize systems such as the Gaitrite (CIR Systems, Sparta, NJ) to measure the many parameters of gait. Measures of gait can be taken during single task (ST) or dual task (DT) scenarios. Overall, concussed individuals tend to adopt a more conservative gait strategy in the sagittal plane.⁶⁷⁻⁶⁹ ST is simply walking at a self-selected “normal” pace. Concussed athletes have greater ML sway compared to non-concussed athletes.⁶¹ Concussed subject had to conservatively adjust their whole body center of mass motion to maintain dynamic stability when walking during ST.⁶² DT can involve cognitive tasks or even physical obstacles the participant must react to while walking. Typically, individuals (both athletes and non-athletes) exhibit a slower gait velocity during DT conditions.⁶¹ However, concussed athletes demonstrate greater medial-lateral sway and sway velocity up to 28 days following the initial injury compared to non-concussed.⁶¹⁻⁶⁴ During obstacle avoidance tasks, concussed participants used a different strategy to clear the obstacles when compared to controls.⁶⁵ This means their ability to orient attention was impaired. Some college-aged individuals showed impairments 4 weeks after suffering a concussion.⁶⁶ These lingering deficits may be absent in ST gait conditions, which shows that DT may be more

sensitive in detecting lasting and minute changes in gait.⁶⁷ Gait analysis has not been conducted to explore the effects of subconcussive impacts in contact athletes.

Recovery

Every concussion is considered as a unique injury and therefore cannot be given a specific timeline as far as recovery and return to play is concerned. There is an ongoing debate whether returning to play is considered recovered or not. Athletes that are returning to play may or may not be fully recovered even though they have passed all of the required tests and have been through a return to play protocol. Normative values for baseline, post concussion, and resolution do exist for a number of typically utilized assessment tools.

On average, graded symptom checklist (GSC) scores of non-concussed individuals is less than 5 points. Graphically, as days pass, a reverse checkmark effect is seen as symptoms start to resolve. Symptom resolution is normally reached by day 7 post injury.^{107,129} SAC scores typically range from 26-28 points prior to concussion.¹⁰⁷ Immediately following injury, there is an average decrease of 3 to 4 points.¹³⁰ Upon repeated post injury testing, scores are seen to return to baseline within 3 administrations or 48 hours post injury. Average BESS scores can vary between 10-13 errors.^{44,107} At the time of concussion, an increase of 6-7 errors is normally seen.^{41,107} Athletes return to their baseline scores in an average of 3-5 days.¹⁰⁷

Though this is representative of the “average” concussion, there are incidences of injuries lasting longer. McCrea et al¹²⁹ showed incidence, recovery pattern, and predictors of prolonged recovery time. Those who fell into the prolonged recovery group had more severe symptoms that

lasted a longer period of time at all assessment points when compared to a “typical” recovery group as well as a control group. Their symptoms remained elevated even through day 45 or 90 following their concussion. SAC scores for this group were lower than the typical group through day 7 where the typical recovery group saw a return to baseline scores by day 2. However, SAC and BESS were not seen to be predictive of prolonged recovery. Their findings suggest that injury marked by unconsciousness, amnesia, and elevated symptoms significantly increase the risk of prolonged recovery time. Players that experienced LOC were 4.15 times more likely, those that suffered from PTA were 1.18 times more likely, and those with retrograde amnesia were 2.19 times more likely to have a prolonged recovery course. Also, players with a GSC increase of 20 or greater were 2.56 times more likely to have a longer recovery.¹²⁹ If there is a lack of resolution in GSC scores within 24-48 hours post injury, this may also be a predictor of a longer recovery. Other studies have shown similar results. Post concussion symptoms scores (PCSS), much like a GSC, has been seen as a predictor when symptoms are greater than 33 points initially and linger for more than 28 days.¹³¹ Lau et al showed that cutoff scores could be used to predict protracted recovery. Migraine symptoms, cognitive symptoms, and visual memory and processing speed on ImPACT testing were all seen to be predictive.¹³²

One common thought is that complete rest until the athlete has become symptom free for a number of days is the best initial plan of action for concussion recovery. This practice is unique to concussion and does not seem to be universally accepted by clinicians or athletes.^{106,133} This practice has little evidence supporting its efficacy. Moser et al were the first to show that prescribed rest, either in the early or late stages of recover, proved effective.¹³⁴ A symptom free waiting period does not matter, rather the total time until the athlete returns to full participation. Athletes that return to participation within 10 days of their initial injury are at a higher risk of

reinjury. Perplexingly, one study concluded that athletes who observed a symptom free waiting period exhibited a higher rate of reinjury.¹⁰⁶ Cognitive rest alone has been shown to be ineffective as well for recovery.¹³⁵ Athletes that engage in school activity as well as light activity (slow jogging or mowing the lawn) may show better scores than athletes with higher or lower levels of mental and physical activity.¹³⁶

Typically, an athlete is seen to have returned to baseline 7-10 days following a concussion when the standard assessment tools are used. There are, of course, individuals that recover much slower. These athletes typically experience LOC, amnesia issues, and higher and prolonged symptoms. During the course of recovery, there is still a debate regarding the practice of a symptom free waiting period, cognitive rest, and physical rest. The time between the injury and return to play seems to be most important since athletes have an increased risk of reinjury within the first 10 days. During recovery, a moderate level of physical activity and normal cognitive activity shows better testing scores and is recommended.

Cumulative Effects And Late Life Problems

Unfortunately, athletes that sustain a concussion are more likely to experience repeated concussions. Within the same season, 7-10 days post injury is seen to be a window of increased susceptibility to reinjury. Of those athletes that sustain repeat concussions, 91.7% of them occur within 10 days and 75% occur within 7 days of the initial concussion.¹³⁷ Though symptom resolution may occur within the same time frame, impairments from a second concussion may be evident up to 30 days after the second concussion occurred.¹³⁸ This is a cause for concern in athletes that play high-risk sports and are exposed for longer periods of time. There are multiple

studies that show correlations between multiple head impacts and issues later in life for athletes, especially NFL players.

The number 3 seems to be prevalent as well as significant in the discussion of cumulative effects of concussion. Individuals that sustain 3 or more concussions are 3-5.8 times more likely to suffer another.¹³⁹ When utilizing ImPACT, those with 3 or more previous concussions have significantly lower verbal memory composite scores, which may also indicate that a dose response exists with incidence of multiple concussions.^{140,141} High school athletes that sustain 3 or more concussions are more likely to experience LOC following a concussion. They are also more likely to demonstrate 3 or 4 abnormal markers such as LOC, PTA, and confusion.¹⁴²

The number 3 continues to be an important link to deficits that arise in late life from the effect of multiple concussions. Those that suffer 3 or more concussions are 5x more likely to have mild cognitive impairment and are 3 times more likely to have memory problems. This is alarming since mild cognitive impairment could be early evidence of chronic traumatic encephalopathy (CTE), though the existence of CTE is still debated.²³ Sadly, the individuals grouped in the 3+ concussion category can also feel the changes that have slowly occurred and claim their injuries have permanently affected their thinking as well as their memory as they aged. Interestingly, and perhaps one of the more startling observations, is the incidence of clinical depression. Athletes with 3 or more concussion are 3 times more likely to be clinically diagnosed with depression. Players that have a history of concussion as well as depression have reported greater physical limitations of activities of daily living. They have also reported more alcohol related problems and are more likely to be separated and divorced.²⁴

Biomechanics of Head Impacts

To better understand what occurs directly to the head during an impact, clinicians and researchers look to more objective means of measuring acceleration forces. Some turn to biomechanical assessments for maximum accuracy. Cameras and video analysis was one of the initial methods in obtaining biomechanical measures of head impacts.^{70,143} Though accurate in its own right, this technique was limited by things such as availability of footage, camera angles, and reconstructability. These limitations led to the need for direct measures of hits. Until recently, technology did not exist to provide direct measures of head impacts.

One of the first studies to measure impacts in football was conducted by Pellman et al⁷⁰. Game film recordings were used to reconstruct concussive impacts that occurred in NFL football games. These analyses were done using crash dummies with accelerometers build into them. Their findings were the basis of direct measurement of head impacts. The average NFL impact that was able to be reconstructed showed a velocity of 9.3 m/s (20.8 MPH), head velocity change of 7.2 m/s (16.1MPH), Severity Index (SI) of 474, and rotational acceleration of 6432 rad/s².⁷⁰ Arguably, the most significant measures of the study were the linear acceleration and duration of the hit. The average NFL concussion had a linear acceleration of 98g and duration of 15 milliseconds. Head impacts in this study showed a strong correlation of concussion with linear acceleration. The relationship between rotational acceleration and concussion seemed to approach significance, suggesting that, with a stronger sample size, rotational acceleration magnitude may also be linked to concussion incidence. However, the main finding suggests that linear acceleration should be the primary measure in the assessment of performance in helmet protection.⁷⁰ A later, more in depth analysis by Pellman et al still showed a significant relationship between translational acceleration. Despite the previous notion that rotational acceleration magnitude may also be related to concussion, this second analysis did not show the

same relationship as before.¹⁴³ To further contradict these findings, Guskiewicz et al showed no relationship between magnitude of both linear and rotational acceleration and symptomology, postural stability, and neuropsychological measures.⁷¹

Of concussive impacts, the majority (61%) involved a hit to the shell of the helmet and 29% involved a hit to the facemask.^{70,143} Impacts to the facemask have the highest average impact velocity, but the lowest change in velocity. The highest rotational acceleration is also associated with facemask hits. 57% of a striking player's helmets occurred at the highest point on the helmet, meaning athletes tend to lower their heads in the act of spearing. This type of hitting is now banned in the NFL. In contrast to hits to the facemask, impacts to the back of the helmet have the lowest impact speed, yet the highest change in velocity.¹⁴³ This is typically seen when a player falls backwards and their head hits the ground in a whiplash-like motion.

In 2003 a system was developed to allow for direct measurement of head impacts in football. It is called the Head Impact Telemetry (HIT) system (Simbex, Lebanon, NH). The HIT System utilizes a helmet insert that has 6 spring-loaded accelerometers that sit against the skull when the helmet is on. The accelerometers are then able to measure linear and rotational forces that occur with head impacts. It is also able to show the specific location on the helmet that the impact occurred as far as section of the helmet and elevation on the helmet. When an impact occurs, the data is sent wirelessly to a laptop computer system. The Riddell Sideline Response System (SRS) is responsible for data collection and analysis in close to "real time." Utilizing this new technology, researchers have conducted studies and compared youth, high school, and collegiate football. Though the level of play is extremely different, the results of some studies are surprising.

In the United States, participation in organized sports is seen in increasing younger ages. Youth football is continuing to grow but, despite a population size of around 3.5 million, head impact exposure has not been heavily investigated. There also tends to be less on-site medical attention is available.^{108,114,144} This is concerning for the safety of the young athletes. Though they are small, the average impact in youth (7-8 years old) football is 18g and 901 rad/s². Even more interesting is that 6 impacts greater than 80g were observed, yet little immediate medical attention is available.¹⁴⁴

High school football accounts for the majority of sport-related concussions that occur in the United States.^{108,114,145} Much like the youth level, high school football had not been studied as often, nor does it have availability of on-site medical attention.¹⁴⁵ Surveys show that as low as 56% of high schools have coverage by a certified athletic trainer.¹⁴⁶ An average of 15-16 impacts occurred per session at this level. The mean impact at the high school level is about 23.8g, which is only approximately 25% higher than youth football.¹⁴⁵ Studies show that impacts occurring to the top of head showed highest magnitude of linear acceleration.¹⁴⁵ This further supports the dangers associated with spearing-like tackling methods.

College football has been the main focus of studies observing the biomechanics of head impacts. 22.3g is the average observed impact sustained at the division I level of play. Similar to the NFL, 102.8g is considered the average concussive impact. These athletes are 6.5 times more likely to sustain an impact of 80g or greater to the top of the head than the sides, though only 0.35% of impacts over 80g resulted in concussion. However, this is still proof that, even though it is illegal, spearing is still taking place. Impacts to the top of the head resulted in some of the larger postural stability deficits and linear accelerations were also greatest in hits to the top of head.^{71,75} Though there is no definitive evidence, a linear acceleration of 98g, based on the

average concussive impacts in the NFL, from the Pellman studies is still used when attempting to set a threshold for concussive impacts. These studies also suggested that impacts of 70-75g are needed to induce concussive injury.^{70,143} Other findings have also suggested the existence of lower thresholds such as a range from 60-80g.⁷¹ However, the dilemma still exists that exceeding one magnitude is directly correlated to concussion. Impacts exceeding 168g and higher have been reported without concussive symptoms.⁷¹ Also, multiple impacts over 90g have been observed without noticeable balance and neurocognitive deficits further showing that no true threshold has yet to be found.¹⁴⁷

The average impact in youth football is only 20% lower than those seen in football players in the Atlantic Coast Conference (ACC). Equally noteworthy is that mean impacts at the high school level are actually higher than those seen in the ACC. This is further evidence against the common thought that “bigger, stronger, faster” athletes are increasing concussion rates.¹⁰⁸

Researchers have also attempted to link the number, magnitude, and location of head impacts to cognitive impairment. The use of the HIT system along with other measures has been used to attempt to correlate the number of blows taken by an athlete and the prevalence of these impairments.^{3,25,30,39,57} A thought exists that a number of subconcussive impacts without clinical presentations of symptoms can lead to measureable deficiencies in postural control and cognition. Players that do not present with clinical S/S may still have measurable impairments. 17% of high school athletes that were not clinically diagnosed with concussion showed impairments in verbal and/or visual memory composites when ImPACT tested during mid-season. This group also exhibited significant decreases in functional magnetic resonance imaging (fMRI) activation levels in regions of the brain strongly associated with working memory.³⁰ This supports the notion that a higher number of impacts sustained may be predictive of

neuropsychological changes.^{3,25} However, there is conflicting evidence to whether these changes are more short-term or long-term.^{25,39} Further, though ImPACT as a stand-alone assessment tool does not exceed 62.5% sensitivity, it is still utilized as such in some studies.⁴⁰ The issue with this, other than the low sensitivity, is that ImPACT has been shown to have a 46% false positive rate.¹⁴⁸

Though many efforts exist, threshold values have not been found for measures seen with the technology. That is to say, a hit that exceeds a specific linear or rotational acceleration cannot definitively prove a concussion has been sustained. This means that, though very accurate and useful, instrumentation such as the HIT System cannot be used diagnostically.^{64,65}

Subconcussive Impacts

Concern regarding the effects of head impacts, both concussive and subconcussive, has been rapidly increasing. Impairment following a concussion has been widely studied with many types of assessments, but little is known about the effects of subconcussive impacts. These hits to the head have the potential to lead to serious detriments. Repetitive blows to the head may be cumulative. Repeat exposure to subconcussive impacts can be linked to pathologically altered neurophysiology, cognitive function, and physiological changes in the brain.³⁻⁶ Therefore, studying potential impairments caused by repetitive subconcussive head impacts may provide insight to potential health risks in the short-term and later in life.

The effects of subconcussive impacts remain conflicted.^{5,19-22} Retired National Football League (NFL) players with a history of 3 or more concussions have an increased likelihood of suffering from late-life difficulties such as: mild cognitive impairment (MCI), depression, and Alzheimer's Disease (AD).^{23,24} However, unlike concussions, there is no established assessment

tool or battery for examining the potential effects of subconcussive impacts. To date, a number of investigators have utilized typical concussion assessment techniques to attempt to measure impairments of subconcussive blows.^{19,20,22} One investigation observed differences in neuropsychological measures between contact and non-contact athletes. This study showed that a higher percentage of contact athletes performed more poorly than predicted on neuropsychological testing when compared to non-contact athletes.²⁵ These decreases in performance were predicted by impact exposure metrics.²⁵ This suggests that there may be a subgroup of individuals that have learning and memory deficits due to repetitive exposure to head impacts.²⁵ A different investigation showed that football athletes had a higher reaction time over the course of a single season. This was proposed to be secondary to subconcussive impacts. These impacts may cause impairments in the brain, particularly the cerebral cortex.⁶

Studies have also investigated the effects of subconcussive head impacts on brain function through imaging techniques. In the course of a single season, high school football athletes with no clinical signs of a concussion showed visual changes in functional Magnetic Resonance Imaging (fMRI).¹⁹ Athletes that may or may not exhibit functional signs of a concussion (i.e. symptoms, postural stability, cognition, and/or neuropsychology as determined by a clinician) also showed visual changes in fMRI.¹⁹ This diagnostic imaging technique measures brain activity based on the blood oxygenation level dependent effect. Blood flow to an area of the brain increases due to a given activity. An fMRI is able to detect oxygenated blood level since blood gives a stronger magnetic signal when it is oxygen-rich.²⁷⁻²⁹ Athletes with a greater number of head impacts were seen to show these changes in oxygenated blood flow.^{3,30} This indicates that subconcussive impacts may play a role in lower activation levels and degenerative changes in the brain.²⁶ Lastly, cumulative head impacts have been shown to have a

significant relationship to diffusion tensor imaging (DTI).⁴ DTI is able to tract subtle changes in white matter over relatively small amounts of time within a single subject.^{4,38} This demonstrates that changes in cognitive function that are related to concussion can be seen in athletes without a clinical diagnosis of concussion.⁴ On the contrary, further studies in have also shown no significant decreases in neuropsychological testing measures and commonly used assessments of balance after the course of one season.^{20,30,39} Therefore, the true effect of subconcussive impacts remains unknown to investigators and further research is needed to better understand the topic. Studying the potential detrimental effects of subconcussive impacts warrants further investigation within other body systems.

Traditionally, an assessment battery of comprised of postural stability, cognition, self-reported symptoms, and neuropsychological testing is highly sensitive in the assessment of concussion.⁴⁰ Investigators have also used these measures in an attempt to assess changes associated with subconcussive head impacts.^{2,19-22,25,26} As mentioned before, neuropsychological testing has been used and, in of particular interest to this investigate, measures of postural stability have been used in these previous investigations.^{2,20,22}

The Balance Error Scoring System (BESS) is widely used by clinicians for the assessment of postural stability and it is popular due to its low cost and practicality.⁴¹ The BESS test is comprised of a total of 6 static stances performed on both a firm surface and foam surface. Any deviations from these stances are counted as “errors” and totaled at the end of the test for an overall score. However, the BESS test has many limitations. It is only seen to be moderately reliable in concussion assessment and has a practice effect associated with serial administration.^{20,43} When using the BESS test for pre- and post-season measures, Division I athletes that sustain subconcussive impacts showed a significant decrease in scores. This implies

an improvement in postural control over the course of one season.⁴⁴ In Division I football players, the same result of increased postural stability has been observed from pre- to post-season.²² A regression model in this study also revealed that the number of head impacts, the cumulative magnitude, and the number of previous concussions sustained were predictors of improved postural stability.³⁹ This further builds the idea of a practice or learning effect with multiple administrations within a relatively short period of time.

Force platforms alone are commonly seen in research to assess changes in postural stability with both linear and non-linear measures.^{10,12,17,22,45,46} Linear measures can be summarized by measures of how far (displacement) and how fast (velocity). These measures, such as center of pressure area and velocity, have shown lingering deficits outside of the typical post-injury window.⁴⁷ This contradicts previous research showing that the BESS test and Sensory Organization Test (SOT) scores return to baseline values within a 3-4 day period following concussive injury.^{107,124,149,150} This is potentially concerning since the BESS test is widely used by clinicians. On the other side, nonlinear measures can also be used to assess changes in postural stability. Unlike linear measures, nonlinear dynamics measures chaos and variability of a signal. Though linear measures may show some lingering deficits, non-linear measures, approximate entropy (ApEn) in particular, have been able to show changes in center of pressure variability where linear measures had not.⁵⁵ Therefore, ApEn may be a more sensitive measure when assessing postural stability when compared to linear measures. ApEn has not been used in the assessment of subconcussive impacts and may warrant investigation.⁵⁷

Several tools are available to help better understand what happens to the head during an impact. The Head Impact Telemetry System (HITS) (Simbex, Lebanon, NH) consists of an encoder with six uniaxial accelerometers. The encoders are inserted into Riddell Revolution and

Riddell Speed model helmets and are able measure the kinematics of helmet impacts. Specifically, it measures linear acceleration, rotational acceleration, and impact location. Each accelerometer continuously samples impacts throughout play during practices and competitions. This allows researchers to have measureable data on each hit that occurs and, potentially, correlate it to deficits that may be seen. As far as concussive impacts, there is still a debate on the theoretical threshold. The mean NFL concussion was seen at 98g when concussive impacts were reconstructed in a laboratory setting.⁷⁰ However, the mean college concussive impact was measured at 102g.⁷¹ The proposed low-end threshold, as of now, is 60-80g.⁷⁰⁻⁷² In the collegiate setting, the average head impact measures at 21g to 22g and can suffer as many as 1400 impacts in a season.⁷³⁻⁷⁵ Typically, an athlete sees between about 950 and 1350 head impacts a season, but this number is largely dependent on the style of offense or defense, play status, and position.^{71,74,76-78} HITS has previously been used in the assessment of subconcussive impacts in collegiate athletes.^{4,19,22,25,26} Variables used in these studies include: total number of impacts, maximal linear and rotational acceleration, maximal HITsp, summation of linear acceleration, summation of rotational acceleration, summation of HITsp, number of impacts of 90g, number of impacts to the top of the head, number of previous concussions, number of years played.^{25,39}

Conclusion

The term and definition of concussion has changed drastically since the first investigators attempted to explain it. This gradual increase in understanding had also caused more complex questions to arise. Though MTBI may not be visible in common imaging techniques, a neurometabolic cascade has been observed and may be consistent with symptom and impairment duration. Now that a better understanding and definition exists, more measures can be taken as far as prevention of injury is concerned.

The incidence of concussion in sport is highly reported. The CDC estimates 1.6-3.8 million concussions occur annually in the United States. LOC, PTA, and certain symptoms (HA, blurred vision, dizziness) are all indicative of concussion. Though common thought is that most concussions occur in high school football, this notion has been shown to be untrue. Also, the concept of “bigger, faster, stronger” is false. Another main concern is coverage, or lack thereof, by athletic trainers at the high school level. Increasing medical coverage at the high school level and below could drastically reduce the danger of concussions, second impact syndrome, and injuries overall.

Objective measures of concussion commonly used by clinicians have been shown to have a high sensitivity and specificity. The testing of these tools on an individual basis has led to important improvements to aid in the diagnosis of concussion. Individually, assessment tools are not adequate enough. When used in conjunction with each other, their sensitivity drastically increases. Therefore, recommendations for the use of a multifaceted approach to the assessment of concussion are continuously being supported by literature. This is widely utilized by athletic training staffs as a means of diagnosis and total recovery.

The track to recovery after a concussion has been highly observed even though each injury is considered to be unique and treated as such. Coaches and fans want concrete numbers for RTP statuses. Average recovery timelines may serve as a suggested schedule for return to play, but cannot be used definitively as there are athletes that fall beyond this range. Though a symptom free waiting period is utilized, it is not supported by the literature. Instead, health care providers should recommend moderate activity levels, such as leisurely activities, and normal cognitive tasks. That is, of course, as long as nothing exacerbates their symptoms. A specific, and individualized protocol should be implemented to ensure full recovery upon returning to

sport participation. In some cases, early return to play can be detrimental due to the prevalence of repeat concussion and more severe injury. The number 3 and cumulative effects of concussions seem to go hand in hand. Those with 3 or more concussions are much more susceptible to a suffering another. They are also more likely to have physical and cognitive impairments later in life. This may include depression, alcohol dependence, memory troubles, and CTE.

To better understand concussions, new technology is continuously being developed and allows researchers to precisely measure the forces that are acting upon the head during impact. The HIT system is one of the most advanced technologies available for the instrumentation of football helmets. Though much of the data that is given from this technology is useful for research, the elusive threshold debate continues. New and better research continues to arise. Some studies bring answers, while others raise more questions.

Aside from concussions, more research is emerging regarding potential detriments associated with subconcussive impacts. Thus far, there is no tool or assessment that is able to accurately and consistently measure deficits due to repetitive head impacts. However, there are some assessments that have shown promise such as ImPACT and measures of postural stability.

References

1. Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. *The Journal of head trauma rehabilitation*. 2006;21(5):375-378.
2. Bailes JE, Petraglia AL, Omalu BI, Nauman E, Talavage T. Role of subconcussion in repetitive mild traumatic brain injury. *Journal of neurosurgery*. 2013;119(5):1235-1245.
3. Breedlove EL, Robinson M, Talavage TM, et al. Biomechanical correlates of symptomatic and asymptomatic neurophysiological impairment in high school football. *J Biomech*. 2012;45(7):1265-1272.
4. Davenport EM, Whitlow CT, Urban JE, et al. Abnormal white matter integrity related to head impact exposure in a season of high school varsity football. *Journal of neurotrauma*. 2014;31(19):1617-1624.
5. Johnson B, Neuberger T, Gay M, Hallett M, Slobounov S. Effects of subconcussive head trauma on the default mode network of the brain. *Journal of neurotrauma*. 2014;31(23):1907-1913.
6. Volberding J, Melvin D. Changes in IMPACT and Graded Symptom Checklist Scores During a Division I Football Season. *Athletic Training & Sports Health Care*. 2014;6(4):6.
7. Broglio SP, Eckner JT, Paulson HL, Kutcher JS. Cognitive decline and aging: the role of concussive and subconcussive impacts. *Exercise and sport sciences reviews*. 2012;40(3):138-144.
8. Buckley TA, Munkasy BA, Tapia-Lovler TG, Wikstrom EA. Altered gait termination strategies following a concussion. *Gait & posture*. 2013;38(3):549-551.
9. Catena RD, van Donkelaar P, Chou LS. Cognitive task effects on gait stability following concussion. *Experimental brain research*. 2007;176(1):23-31.
10. Catena RD, van Donkelaar P, Chou LS. Altered balance control following concussion is better detected with an attention test during gait. *Gait & posture*. 2007;25(3):406-411.
11. Catena RD, van Donkelaar P, Halterman CI, Chou LS. Spatial orientation of attention and obstacle avoidance following concussion. *Experimental brain research*. 2009;194(1):67-77.
12. Guskiewicz KM, Ross SE, Marshall SW. Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes. *Journal of athletic training*. 2001;36(3):263-273.
13. Parker TM, Osternig LR, Lee HJ, Donkelaar P, Chou LS. The effect of divided attention on gait stability following concussion. *Clinical biomechanics*. 2005;20(4):389-395.
14. Parker TM, Osternig LR, P VAND, Chou LS. Gait stability following concussion. *Medicine and science in sports and exercise*. 2006;38(6):1032-1040.
15. Parker TM, Osternig LR, van Donkelaar P, Chou LS. Recovery of cognitive and dynamic motor function following concussion. *British journal of sports medicine*. 2007;41(12):868-873; discussion 873.
16. Parker TM, Osternig LR, van Donkelaar P, Chou LS. Balance control during gait in athletes and non-athletes following concussion. *Medical engineering & physics*. 2008;30(8):959-967.
17. Powers KC, Kalmar JM, Cinelli ME. Recovery of static stability following a concussion. *Gait & posture*. 2014;39(1):611-614.
18. Powers KC, Kalmar JM, Cinelli ME. Dynamic stability and steering control following a sport-induced concussion. *Gait & posture*. 2014;39(2):728-732.
19. Breedlove EL, Robinson M, Talavage TM, et al. Biomechanical correlates of symptomatic and asymptomatic neurophysiological impairment in high school football. *Journal of biomechanics*. 2012;45(7):1265-1272.
20. Burk JM, Munkasy BA, Joyner AB, Buckley TA. Balance error scoring system performance changes after a competitive athletic season. *Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine*. 2013;23(4):312-317.

21. Dashnaw ML, Petraglia AL, Bailes JE. An overview of the basic science of concussion and subconcussion: where we are and where we are going. *Neurosurgical focus*. 2012;33(6):E5: 1-9.
22. Gysland SM, Mihalik JP, Register-Mihalik JK, Trulock SC, Shields EW, Guskiewicz KM. The relationship between subconcussive impacts and concussion history on clinical measures of neurologic function in collegiate football players. *Annals of biomedical engineering*. 2012;40(1):14-22.
23. Guskiewicz KM, Marshall SW, Bailes J, et al. Association between recurrent concussion and late-life cognitive impairment in retired professional football players. *Neurosurgery*. 2005;57(4):719-726; discussion 719-726.
24. Guskiewicz KM, Marshall SW, Bailes J, et al. Recurrent concussion and risk of depression in retired professional football players. *Med Sci Sports Exerc*. 2007;39(6):903-909.
25. McAllister TW, Flashman LA, Maerlender A, et al. Cognitive effects of one season of head impacts in a cohort of collegiate contact sport athletes. *Neurology*. 2012;78(22):1777-1784.
26. Talavage TM, Nauman EA, Breedlove EL, et al. Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion. *Journal of neurotrauma*. 2014;31(4):327-338.
27. Buxton RB. *Introduction to functional magnetic resonance imaging : principles and techniques*. 2nd ed. Cambridge ; New York: Cambridge University Press; 2009.
28. Codrington-Lacerte C. *Functional magnetic resonance imaging*. Salem Press; 2013.
29. Smith K. Brain imaging: fMRI 2.0. *Nature*. 2012;484(7392):24-26.
30. Talavage TM, Nauman EA, Breedlove EL, et al. Functionally-Detected Cognitive Impairment in High School Football Players Without Clinically-Diagnosed Concussion. *J Neurotrauma*. 2013.
31. Gruber O, von Cramon DY. The functional neuroanatomy of human working memory revisited. Evidence from 3-T fMRI studies using classical domain-specific interference tasks. *NeuroImage*. 2003;19(3):797-809.
32. Kwon H, Reiss AL, Menon V. Neural basis of protracted developmental changes in visuo-spatial working memory. *Proceedings of the National Academy of Sciences of the United States of America*. 2002;99(20):13336-13341.
33. Assaf Y, Pasternak O. Diffusion tensor imaging (DTI)-based white matter mapping in brain research: a review. *Journal of molecular neuroscience : MN*. 2008;34(1):51-61.
34. Basser PJ. Inferring microstructural features and the physiological state of tissues from diffusion-weighted images. *NMR in biomedicine*. 1995;8(7-8):333-344.
35. Basser PJ, Mattiello J, LeBihan D. MR diffusion tensor spectroscopy and imaging. *Biophysical journal*. 1994;66(1):259-267.
36. Basser PJ, Pierpaoli C. Microstructural and physiological features of tissues elucidated by quantitative-diffusion-tensor MRI. *Journal of magnetic resonance. Series B*. 1996;111(3):209-219.
37. Basser PJ, Pierpaoli C. A simplified method to measure the diffusion tensor from seven MR images. *Magnetic resonance in medicine : official journal of the Society of Magnetic Resonance in Medicine / Society of Magnetic Resonance in Medicine*. 1998;39(6):928-934.
38. Farrell JA, Landman BA, Jones CK, et al. Effects of signal-to-noise ratio on the accuracy and reproducibility of diffusion tensor imaging-derived fractional anisotropy, mean diffusivity, and principal eigenvector measurements at 1.5 T. *Journal of magnetic resonance imaging : JMRI*. 2007;26(3):756-767.
39. Gysland SM, Mihalik JP, Register-Mihalik JK, Trulock SC, Shields EW, Guskiewicz KM. The relationship between subconcussive impacts and concussion history on clinical measures of neurologic function in collegiate football players. *Ann Biomed Eng*. 2012;40(1):14-22.

40. Broglio SP, Macciocchi SN, Ferrara MS. Sensitivity of the concussion assessment battery. *Neurosurgery*. 2007;60(6):1050-1057; discussion 1057-1058.
41. Finnoff JT, Peterson VJ, Hollman JH, Smith J. Intrarater and interrater reliability of the Balance Error Scoring System (BESS). *Pm R*. 2009;1(1):50-54.
42. Broglio SP, Cantu RC, Gioia GA, et al. National Athletic Trainers' Association position statement: management of sport concussion. *Journal of athletic training*. 2014;49(2):245-265.
43. Finnoff JT, Peterson VJ, Hollman JH, Smith J. Intrarater and interrater reliability of the Balance Error Scoring System (BESS). *PM & R : the journal of injury, function, and rehabilitation*. 2009;1(1):50-54.
44. Burk JM, Munkasy BA, Joyner AB, Buckley TA. Balance error scoring system performance changes after a competitive athletic season. *Clin J Sport Med*. 2013;23(4):312-317.
45. Cavanaugh JT, Mercer VS, Stergiou N. Approximate entropy detects the effect of a secondary cognitive task on postural control in healthy young adults: a methodological report. *Journal of neuroengineering and rehabilitation*. 2007;4:42.
46. Riemann BL, Guskiewicz KM. Effects of mild head injury on postural stability as measured through clinical balance testing. *Journal of athletic training*. 2000;35(1):19-25.
47. Powers KC, Kalmar JM, Cinelli ME. Recovery of static stability following a concussion. *Gait Posture*. 2013.
48. Guskiewicz KM, Riemann BL, Perrin DH, Nashner LM. Alternative approaches to the assessment of mild head injury in athletes. *Medicine and science in sports and exercise*. 1997;29(7 Suppl):S213-221.
49. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *Jama*. 2003;290(19):2556-2563.
50. Cavanaugh JT, Guskiewicz KM, Giuliani C, Marshall S, Mercer VS, Stergiou N. Recovery of postural control after cerebral concussion: new insights using approximate entropy. *Journal of athletic training*. 2006;41(3):305-313.
51. Cavanaugh JT, Guskiewicz KM, Giuliani C, Marshall S, Mercer V, Stergiou N. Detecting altered postural control after cerebral concussion in athletes with normal postural stability. *British journal of sports medicine*. 2005;39(11):805-811.
52. Cavanaugh JT, Guskiewicz KM, Stergiou N. A nonlinear dynamic approach for evaluating postural control: new directions for the management of sport-related cerebral concussion. *Sports medicine*. 2005;35(11):935-950.
53. Granata KP, England SA. Reply to the Letter to the Editor. *Gait & posture*. 2007;26:329-330.
54. Stergiou N, Decker LM. Human movement variability, nonlinear dynamics, and pathology: is there a connection? *Human movement science*. 2011;30(5):869-888.
55. Cavanaugh JT, Mercer VS, Stergiou N. Approximate entropy detects the effect of a secondary cognitive task on postural control in healthy young adults: a methodological report. *J Neuroeng Rehabil*. 2007;4:42.
56. Pincus SM, Goldberger AL. Physiological time-series analysis: what does regularity quantify? *The American journal of physiology*. 1994(4):1643.
57. Broglio SP, Eckner JT, Paulson HL, Kutcher JS. Cognitive decline and aging: the role of concussive and subconcussive impacts. *Exerc Sport Sci Rev*. 2012;40(3):138-144.
58. Kuys SS, Brauer SG, Ada L. Test-retest reliability of the GAITRite system in people with stroke undergoing rehabilitation. *Disability and rehabilitation*. 2011;33(19-20):1848-1853.
59. Greene BR, Foran TG, McGrath D, Doheny EP, Burns A, Caulfield B. A comparison of algorithms for body-worn sensor-based spatiotemporal gait parameters to the GAITRite electronic walkway. *Journal of applied biomechanics*. 2012;28(3):349-355.

60. Martini DN, Sabin MJ, DePesa SA, et al. The chronic effects of concussion on gait. *Archives of physical medicine and rehabilitation*. 2011;92(4):585-589.
61. Parker TM, Osternig LR, van Donkelaar P, Chou LS. Balance control during gait in athletes and non-athletes following concussion. *Med Eng Phys*. 2008;30(8):959-967.
62. Parker TM, Osternig LR, Lee HJ, Donkelaar P, Chou LS. The effect of divided attention on gait stability following concussion. *Clin Biomech (Bristol, Avon)*. 2005;20(4):389-395.
63. Catena RD, van Donkelaar P, Chou LS. Altered balance control following concussion is better detected with an attention test during gait. *Gait Posture*. 2007;25(3):406-411.
64. Parker TM, Osternig LR, van Donkelaar P, Chou LS. Recovery of cognitive and dynamic motor function following concussion. *Br J Sports Med*. 2007;41(12):868-873; discussion 873.
65. Catena RD, van Donkelaar P, Halterman CI, Chou LS. Spatial orientation of attention and obstacle avoidance following concussion. *Experimental brain research*. 2009;194(1):67-77.
66. Parker TM, Osternig LR, P VAND, Chou LS. Gait stability following concussion. *Med Sci Sports Exerc*. 2006;38(6):1032-1040.
67. Catena RD, van Donkelaar P, Chou LS. Different gait tasks distinguish immediate vs. long-term effects of concussion on balance control. *J Neuroeng Rehabil*. 2009;6:25.
68. Catena RD, van Donkelaar P, Chou LS. Cognitive task effects on gait stability following concussion. *Experimental brain research*. 2007;176(1):23-31.
69. Martini DN, Sabin MJ, DePesa SA, et al. The chronic effects of concussion on gait. *Arch Phys Med Rehabil*. 2011;92(4):585-589.
70. Pellman EJ, Viano DC, Tucker AM, Casson IR, Waeckerle JF. Concussion in professional football: reconstruction of game impacts and injuries. *Neurosurgery*. 2003;53(4):799-812; discussion 812-794.
71. Guskiewicz KM, Mihalik JP, Shankar V, et al. Measurement of head impacts in collegiate football players: relationship between head impact biomechanics and acute clinical outcome after concussion. *Neurosurgery*. 2007;61(6):1244-1252; discussion 1252-1243.
72. Hugenholtz H, Richard MT. Return to athletic competition following concussion. *Can Med Assoc J*. 1982;127(9):827-829.
73. Brolinson PG, Manoogian S, McNeely D, Goforth M, Greenwald R, Duma S. Analysis of linear head accelerations from collegiate football impacts. *Curr Sports Med Rep*. 2006;5(1):23-28.
74. Crisco JJ, Fiore R, Beckwith JG, et al. Frequency and location of head impact exposures in individual collegiate football players. *J Athl Train*. 2010;45(6):549-559.
75. Mihalik JP, Bell DR, Marshall SW, Guskiewicz KM. Measurement of head impacts in collegiate football players: an investigation of positional and event-type differences. *Neurosurgery*. 2007;61(6):1229-1235; discussion 1235.
76. Bailes JE, Petraglia AL, Omalu BI, Nauman E, Talavage T. Role of subconcussion in repetitive mild traumatic brain injury. *J Neurosurg*. 2013;119(5):1235-1245.
77. Guskiewicz KM, Mihalik JP. Biomechanics of sport concussion: quest for the elusive injury threshold. *Exerc Sport Sci Rev*. 2011;39(1):4-11.
78. Schnebel B, Gwin JT, Anderson S, Gatlin R. In vivo study of head impacts in football: a comparison of National Collegiate Athletic Association Division I versus high school impacts. *Neurosurgery*. 2007;60(3):490-495; discussion 495-496.
79. Beckwith JG, Greenwald RM, Chu JJ, et al. Timing of concussion diagnosis is related to head impact exposure prior to injury. *Medicine and science in sports and exercise*. 2013;45(4):747-754.
80. Marjoux D, Baumgartner D, Deck C, Willinger R. Head injury prediction capability of the HIC, HIP, SIMon and ULP criteria. *Accident; analysis and prevention*. 2008;40(3):1135-1148.

81. Jadischke R, Viano DC, Dau N, King AI, McCarthy J. On the accuracy of the Head Impact Telemetry (HIT) System used in football helmets. *Journal of biomechanics*. 2013;46(13):2310-2315.
82. Register-Mihalik JK, Mihalik JP, Guskiewicz KM. Balance deficits after sports-related concussion in individuals reporting posttraumatic headache. *Neurosurgery*. 2008;63(1):76-80; discussion 80-72.
83. Beckwith JG, Greenwald RM, Chu JJ. Measuring head kinematics in football: correlation between the head impact telemetry system and Hybrid III headform. *Annals of biomedical engineering*. 2012;40(1):237-248.
84. Clark RA, Bower KJ, Mentiplay BF, Paterson K, Pua YH. Concurrent validity of the Microsoft Kinect for assessment of spatiotemporal gait variables. *J Biomech*. 2013;46(15):2722-2725.
85. Greene BR, Foran TG, McGrath D, Doheny EP, Burns A, Caulfield B. A comparison of algorithms for body-worn sensor-based spatiotemporal gait parameters to the GAITRite electronic walkway. *J Appl Biomech*. 2012;28(3):349-355.
86. Kuys SS, Brauer SG, Ada L. Test-retest reliability of the GAITRite system in people with stroke undergoing rehabilitation. *Disabil Rehabil*. 2011;33(19-20):1848-1853.
87. Bressel E, Yonker JC, Kras J, Heath EM. Comparison of static and dynamic balance in female collegiate soccer, basketball, and gymnastics athletes. *Journal of athletic training*. 2007;42(1):42-46.
88. Sekiya N, Nagasaki H, Ito H, Furuna T. Optimal walking in terms of variability in step length. *The Journal of orthopaedic and sports physical therapy*. 1997;26(5):266-272.
89. Judge JO, Davis RB, 3rd, Ounpuu S. Step length reductions in advanced age: the role of ankle and hip kinetics. *The journals of gerontology. Series A, Biological sciences and medical sciences*. 1996;51(6):M303-312.
90. Broglio SP, Pontifex MB, O'Connor P, Hillman CH. The persistent effects of concussion on neuroelectric indices of attention. *Journal of neurotrauma*. 2009;26(9):1463-1470.
91. Bryan CJ, Clemans TA. Repetitive traumatic brain injury, psychological symptoms, and suicide risk in a clinical sample of deployed military personnel. *JAMA psychiatry*. 2013;70(7):686-691.
92. De Beaumont L, Brisson B, Lassonde M, Jolicoeur P. Long-term electrophysiological changes in athletes with a history of multiple concussions. *Brain injury : [BI]*. 2007;21(6):631-644.
93. Guskiewicz KM, Marshall SW, Bailes J, et al. Recurrent concussion and risk of depression in retired professional football players. *Medicine and science in sports and exercise*. 2007;39(6):903-909.
94. McKee AC, Cantu RC, Nowinski CJ, et al. Chronic traumatic encephalopathy in athletes: progressive tauopathy after repetitive head injury. *Journal of neuropathology and experimental neurology*. 2009;68(7):709-735.
95. McKee AC, Stern RA, Nowinski CJ, et al. The spectrum of disease in chronic traumatic encephalopathy. *Brain : a journal of neurology*. 2013;136(Pt 1):43-64.
96. Donchin E, Coles MG. Is the P300 component a manifestation of context updating? *Behavioral and Brain Sciences*. 1988;11(3):357-427.
97. Johnson R, Jr., Donchin E. On how P300 amplitude varies with the utility of the eliciting stimuli. *Electroencephalography and clinical neurophysiology*. 1978;44(4):424-437.
98. Chrisman SP, Schiff MA, Rivara FP. Physician concussion knowledge and the effect of mailing the CDC's "Heads Up" toolkit. *Clin Pediatr (Phila)*. 2011;50(11):1031-1039.
99. Lannsjo M, Backheden M, Johansson U, Af Geijerstam JL, Borg J. Does head CT scan pathology predict outcome after mild traumatic brain injury? *Eur J Neurol*. 2013;20(1):124-129.

100. Kutcher JS, McCrory P, Davis G, Ptito A, Meeuwisse WH, Broglio SP. What evidence exists for new strategies or technologies in the diagnosis of sports concussion and assessment of recovery? *Br J Sports Med.* 2013;47(5):299-303.
101. Llewellyn T, Burdette GT, Joyner AB, Buckley TA. Concussion Reporting Rates at the Conclusion of an Intercollegiate Athletic Career. *Clin J Sport Med.* 2013.
102. Valovich McLeod TC, Schwartz C, Bay RC. Sport-related concussion misunderstandings among youth coaches. *Clin J Sport Med.* 2007;17(2):140-142.
103. Cantu RC. Second-impact syndrome. *Clin Sports Med.* 1998;17(1):37-44.
104. Mccrory P, berkovic S. The History of Clinical and Pathophysiological Concepts and Misconceptions. *Neurology.* 2008;57:2283-2289.
105. Giza CC, Hovda DA. The Neurometabolic Cascade of Concussion. *J Athl Train.* 2001;36(3):228-235.
106. McCrea M, Guskiewicz K, Randolph C, et al. Effects of a symptom-free waiting period on clinical outcome and risk of reinjury after sport-related concussion. *Neurosurgery.* 2009;65(5):876-882; discussion 882-873.
107. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *Jama.* 2003;290(19):2556-2563.
108. Guskiewicz KM, Weaver NL, Padua DA, Garrett WE, Jr. Epidemiology of concussion in collegiate and high school football players. *Am J Sports Med.* 2000;28(5):643-650.
109. Register-Mihalik JK, Guskiewicz KM, McLeod TC, Linnan LA, Mueller FO, Marshall SW. Knowledge, attitude, and concussion-reporting behaviors among high school athletes: a preliminary study. *J Athl Train.* 2013;48(5):645-653.
110. Saunders EA, Burdette GT, Metzler JN, Joyner AB, Buckley TA. Knowledge of Coaching Education Students Regarding Sport-Related Concussions. *Athletic Training & Sports Health Care: The Journal for the Practicing Clinician.* 2013;5(1):11-19.
111. Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. *J Head Trauma Rehabil.* 2006;21(5):375-378.
112. Shankar PR, Fields SK, Collins CL, Dick RW, Comstock RD. Epidemiology of high school and collegiate football injuries in the United States, 2005-2006. *Am J Sports Med.* 2007;35(8):1295-1303.
113. Gessel LM, Fields SK, Collins CL, Dick RW, Comstock RD. Concussions among United States high school and collegiate athletes. *J Athl Train.* 2007;42(4):495-503.
114. Powell JW, Barber-Foss KD. Traumatic brain injury in high school athletes. *Jama.* 1999;282(10):958-963.
115. Marar M, McIlvain NM, Fields SK, Comstock RD. Epidemiology of concussions among United States high school athletes in 20 sports. *Am J Sports Med.* 2012;40(4):747-755.
116. Covassin T, Swanik CB, Sachs ML. Sex Differences and the Incidence of Concussions Among Collegiate Athletes. *J Athl Train.* 2003;38(3):238-244.
117. Maddocks DL, Dicker GD, Saling MM. The assessment of orientation following concussion in athletes. *Clin J Sport Med.* 1995;5(1):32-35.
118. Shores EA, Marosszeky JE, Sandanam J, Batchelor J. Preliminary validation of a clinical scale for measuring the duration of post-traumatic amnesia. *Med J Aust.* 1986;144(11):569-572.
119. Yarnell PR, Lynch S. The 'ding': amnesic states in football trauma. *Neurology.* 1973;23(2):196-197.
120. Delaney JS, Lacroix VJ, Leclerc S, Johnston KM. Concussions among university football and soccer players. *Clin J Sport Med.* 2002;12(6):331-338.

121. McCrea M, Kelly JP, Randolph C, Cisler R, Berger L. Immediate neurocognitive effects of concussion. *Neurosurgery*. 2002;50(5):1032-1040; discussion 1040-1032.
122. McCrea M, Kelly JP, Kluge J, Ackley B, Randolph C. Standardized assessment of concussion in football players. *Neurology*. 1997;48(3):586-588.
123. McCrea M, Kelly JP, Randolph C, et al. Standardized assessment of concussion (SAC): on-site mental status evaluation of the athlete. *J Head Trauma Rehabil*. 1998;13(2):27-35.
124. Riemann BL, Guskiewicz KM. Effects of mild head injury on postural stability as measured through clinical balance testing. *J Athl Train*. 2000;35(1):19-25.
125. Valovich McLeod TC, Perrin DH, Guskiewicz KM, Shultz SJ, Diamond R, Gansneder BM. Serial administration of clinical concussion assessments and learning effects in healthy young athletes. *Clin J Sport Med*. 2004;14(5):287-295.
126. Bell DR, Guskiewicz KM, Clark MA, Padua DA. Systematic review of the balance error scoring system. *Sports health*. 2011;3(3):287-295.
127. Register-Mihalik JK, Guskiewicz KM, Mihalik JP, Schmidt JD, Kerr ZY, McCrea MA. Reliable change, sensitivity, and specificity of a multidimensional concussion assessment battery: implications for caution in clinical practice. *J Head Trauma Rehabil*. 2013;28(4):274-283.
128. Guskiewicz KM, Bruce SL, Cantu RC, et al. National Athletic Trainers' Association Position Statement: Management of Sport-Related Concussion. *J Athl Train*. 2004;39(3):280-297.
129. McCrea M, Guskiewicz K, Randolph C, et al. Incidence, clinical course, and predictors of prolonged recovery time following sport-related concussion in high school and college athletes. *J Int Neuropsychol Soc*. 2013;19(1):22-33.
130. McCrea M, Barr WB, Guskiewicz K, et al. Standard regression-based methods for measuring recovery after sport-related concussion. *J Int Neuropsychol Soc*. 2005;11(1):58-69.
131. Meehan WP, 3rd, Mannix RC, Straccioli A, Elbin RJ, Collins MW. Symptom severity predicts prolonged recovery after sport-related concussion, but age and amnesia do not. *J Pediatr*. 2013;163(3):721-725.
132. Lau BC, Collins MW, Lovell MR. Cutoff scores in neurocognitive testing and symptom clusters that predict protracted recovery from concussions in high school athletes. *Neurosurgery*. 2012;70(2):371-379; discussion 379.
133. Ferrara MS, McCrea M, Peterson CL, Guskiewicz KM. A Survey of Practice Patterns in Concussion Assessment and Management. *J Athl Train*. 2001;36(2):145-149.
134. Moser RS, Glatts C, Schatz P. Efficacy of immediate and delayed cognitive and physical rest for treatment of sports-related concussion. *J Pediatr*. 2012;161(5):922-926.
135. Gibson S, Nigrovic LE, O'Brien M, Meehan WP, 3rd. The effect of recommending cognitive rest on recovery from sport-related concussion. *Brain Inj*. 2013;27(7-8):839-842.
136. Majerske CW, Mihalik JP, Ren D, et al. Concussion in sports: postconcussive activity levels, symptoms, and neurocognitive performance. *J Athl Train*. 2008;43(3):265-274.
137. Guskiewicz KM, McCrea M, Marshall SW, et al. Cumulative effects associated with recurrent concussion in collegiate football players: the NCAA Concussion Study. *Jama*. 2003;290(19):2549-2555.
138. Slobounov S, Slobounov E, Sebastianelli W, Cao C, Newell K. Differential rate of recovery in athletes after first and second concussion episodes. *Neurosurgery*. 2007;61(2):338-344; discussion 344.
139. Zemper ED. Two-year prospective study of relative risk of a second cerebral concussion. *Am J Phys Med Rehabil*. 2003;82(9):653-659.
140. Eisenberg MA, Andrea J, Meehan W, Mannix R. Time interval between concussions and symptom duration. *Pediatrics*. 2013;132(1):8-17.

141. Iverson GL, Brooks BL, Lovell MR, Collins MW. No cumulative effects for one or two previous concussions. *Br J Sports Med*. 2006;40(1):72-75.
142. Collins MW, Lovell MR, Iverson GL, Cantu RC, Maroon JC, Field M. Cumulative effects of concussion in high school athletes. *Neurosurgery*. 2002;51(5):1175-1179; discussion 1180-1171.
143. Pellman EJ, Viano DC, Tucker AM, Casson IR. Concussion in professional football: location and direction of helmet impacts-Part 2. *Neurosurgery*. 2003;53(6):1328-1340; discussion 1340-1321.
144. Daniel RW, Rowson S, Duma SM. Head impact exposure in youth football. *Ann Biomed Eng*. 2012;40(4):976-981.
145. Broglio SP, Sosnoff JJ, Shin S, He X, Alcaraz C, Zimmerman J. Head impacts during high school football: a biomechanical assessment. *J Athl Train*. 2009;44(4):342-349.
146. Aukerman DF, Aukerman MM, Browning D. Medical coverage of high school athletics in North Carolina. *South Med J*. 2006;99(2):132-136.
147. McCaffrey MA, Mihalik JP, Crowell DH, Shields EW, Guskiewicz KM. Measurement of head impacts in collegiate football players: clinical measures of concussion after high- and low-magnitude impacts. *Neurosurgery*. 2007;61(6):1236-1243; discussion 1243.
148. Resch J, Driscoll A, McCaffrey N, et al. ImPact test-retest reliability: reliably unreliable? *J Athl Train*. 2013;48(4):506-511.
149. Guskiewicz KM, Ross SE, Marshall SW. Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes. *J Athl Train*. 2001;36(3):263-273.
150. Guskiewicz KM, Riemann BL, Perrin DH, Nashner LM. Alternative approaches to the assessment of mild head injury in athletes. *Med Sci Sports Exerc*. 1997;29(7 Suppl):S213-221.

APPENDIX C

TABLES and FIGURES of RESULTS

Group	Age (yrs)	Gender	Height (cm)	Mass (kg)	Concussion History
SUBC	20.40 \pm 1.12	15 M, 0 F	183.90 \pm 7.61	100.32 \pm 22.08	0.60 \pm 0.83
CONT	19.85 \pm 1.21	2 M, 11 F	161.19 \pm 9.31	58.30 \pm 10.51	0.8 \pm 0.99

Table 1. Subject demographics; group means \pm standard deviation

Group	Mean Number of Impacts	Cumulative Linear Acceleration (g)	Mean Linear Acceleration (g)	Cumulative Rotational Acceleration (rad/sec ²)	Mean Rotational Acceleration (rad/sec ²)	Head Impact Criterion
SUBC	622.27 ± 515.46	18,042.95 ± 15,811.89	26.90 ± 3.11	61,1298.13 ± 49,9510.34	949.18 ± 197.00	13,670.61 ± 13,945.79

Table 2. Normative values for Head Impact Telemetry System; group means ± standard deviation

Group (Time)	BESS (Total Errors)
SUBC Pre	16.47 \pm 7.39
CONT Pre	9.44 \pm 5.96*
SUBC Post	14.20 \pm 7.60
CONT Post	9.31 \pm 4.33*

Table 3. Normative values for the Balance Error Scoring System (BESS) at preseason and postseason; group means \pm standard deviation.

** Significantly lower between groups*

Group (Time)	SLST (cm)	SLDT (cm)	SRST (steps/min)	SRDT (steps /min)
SUBC Pre	68.13 ± 6.16	62.95 ± 7.76	111.91 ± 9.88*	101.36 ± 10.99
CONT Pre	64.95 ± 4.39	61.22 ± 5.28	119.28 ± 7.87	106.42 ± 8.20
SUBC Post	68.51 ± 6.44 ^a	65.42 ± 8.52	111.30 ± 8.39*	105.67 ± 7.51*
CONT Post	65.62 ± 5.15 ^a	62.05 ± 5.45	121.05 ± 9.05	111.39 ± 8.11

Table 4. Normative values for gait measures pre- and posttest; group means ± standard deviation

**Significantly lower between groups*

^aSignificant increase from preseason to postseason

^bSignificant decrease from preseason to postseason

Group (Time)	RAP (ApEn)	RML (ApEn)	LAP (ApEn)	LML (ApEn)	DLAP (ApEn)	DLML (ApEn)
SUBC Pre	0.81 ± 0.12	0.92 ± 0.06	0.77 ± 0.11	0.92 ± 0.09	0.56 ± 0.14	0.55 ± 0.14
CONT Pre	0.74 ± 0.12	0.93 ± 0.06	0.70 ± 0.11	0.90 ± 0.07	0.55 ± 0.06	0.62 ± 0.08
SUBC Post	0.80 ± 0.11	0.91 ± 0.07	0.79 ± 0.14 ^a	0.90 ± 0.05	0.52 ± 0.132	0.59 ± 0.09 ^a
CONT Post	0.77 ± 0.11	0.94 ± 0.08	0.81 ± 0.10 ^a	0.92 ± 0.06	0.53 ± 0.11	0.69 ± 0.09

Table 5. Normative values for static stance measures pre- and posttest; group means ± standard deviation

^a*Significant increase from preseason to postseason*

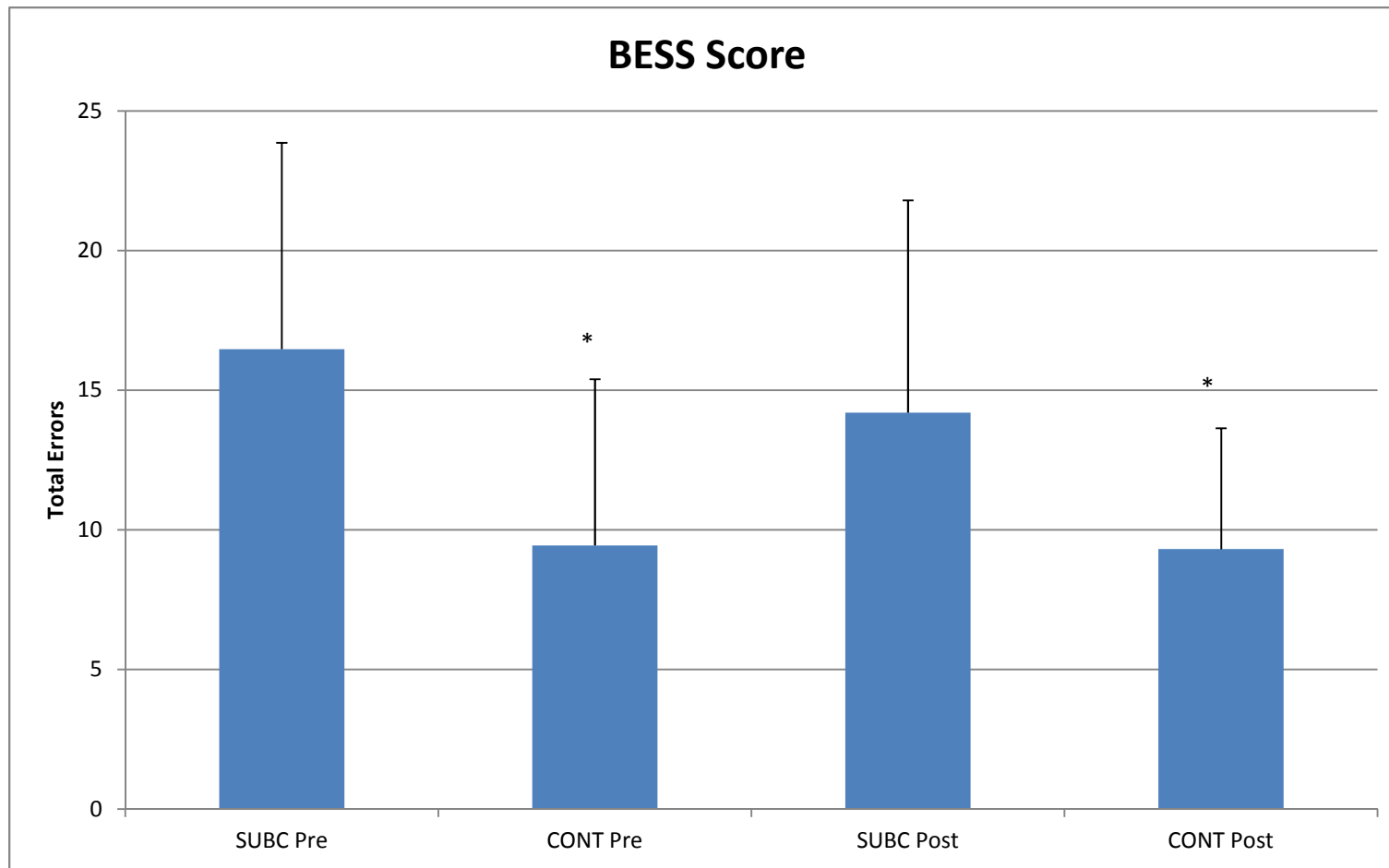


Figure 1. Balance Error Scoring System (BESS) total score at preseason and postseason; group means \pm standard deviation

*Significantly lower between groups

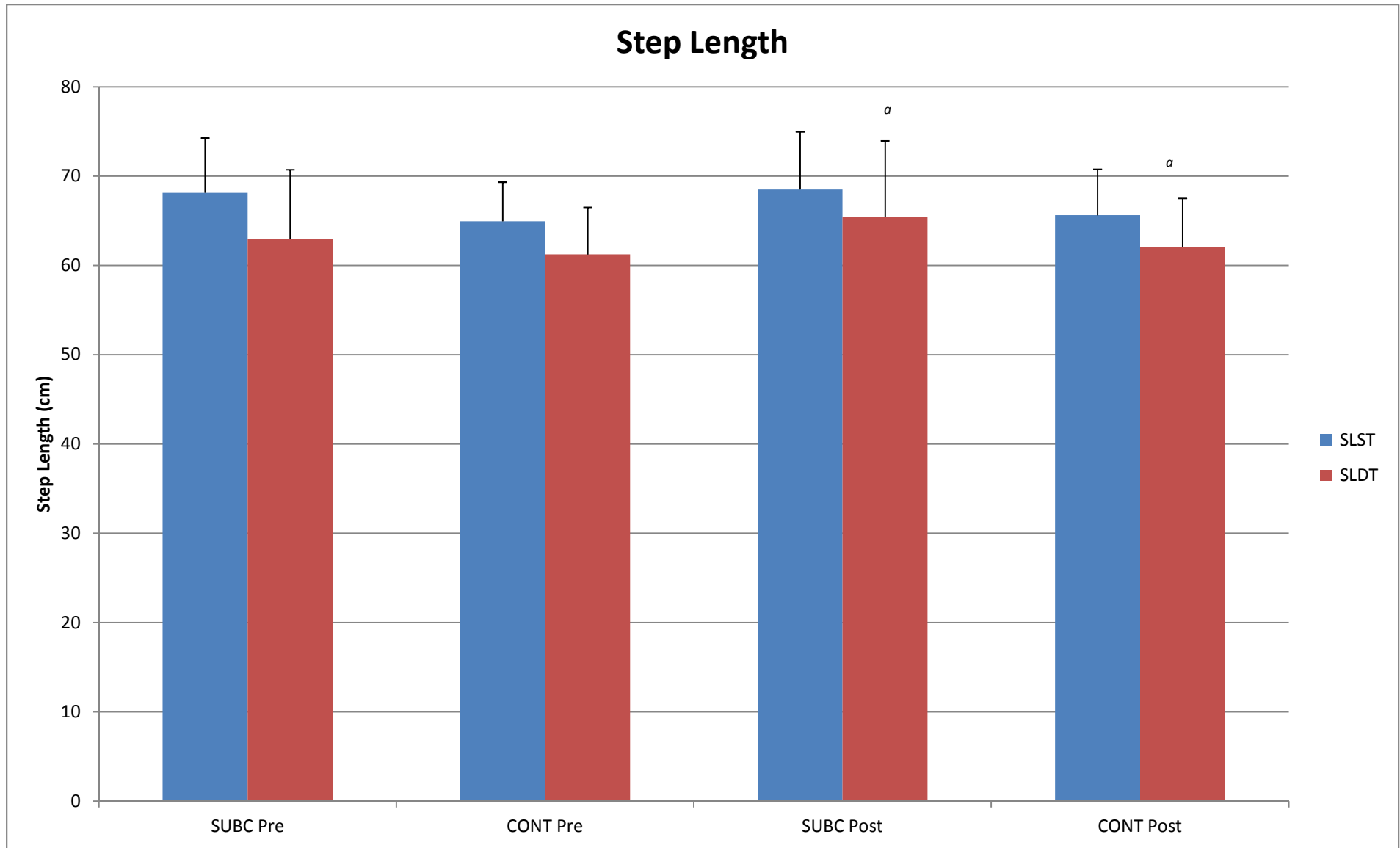


Figure 2. Step length at preseason (Pre) and postseason (Post); group means \pm standard deviation

^aSignificant increase from preseason to postseason

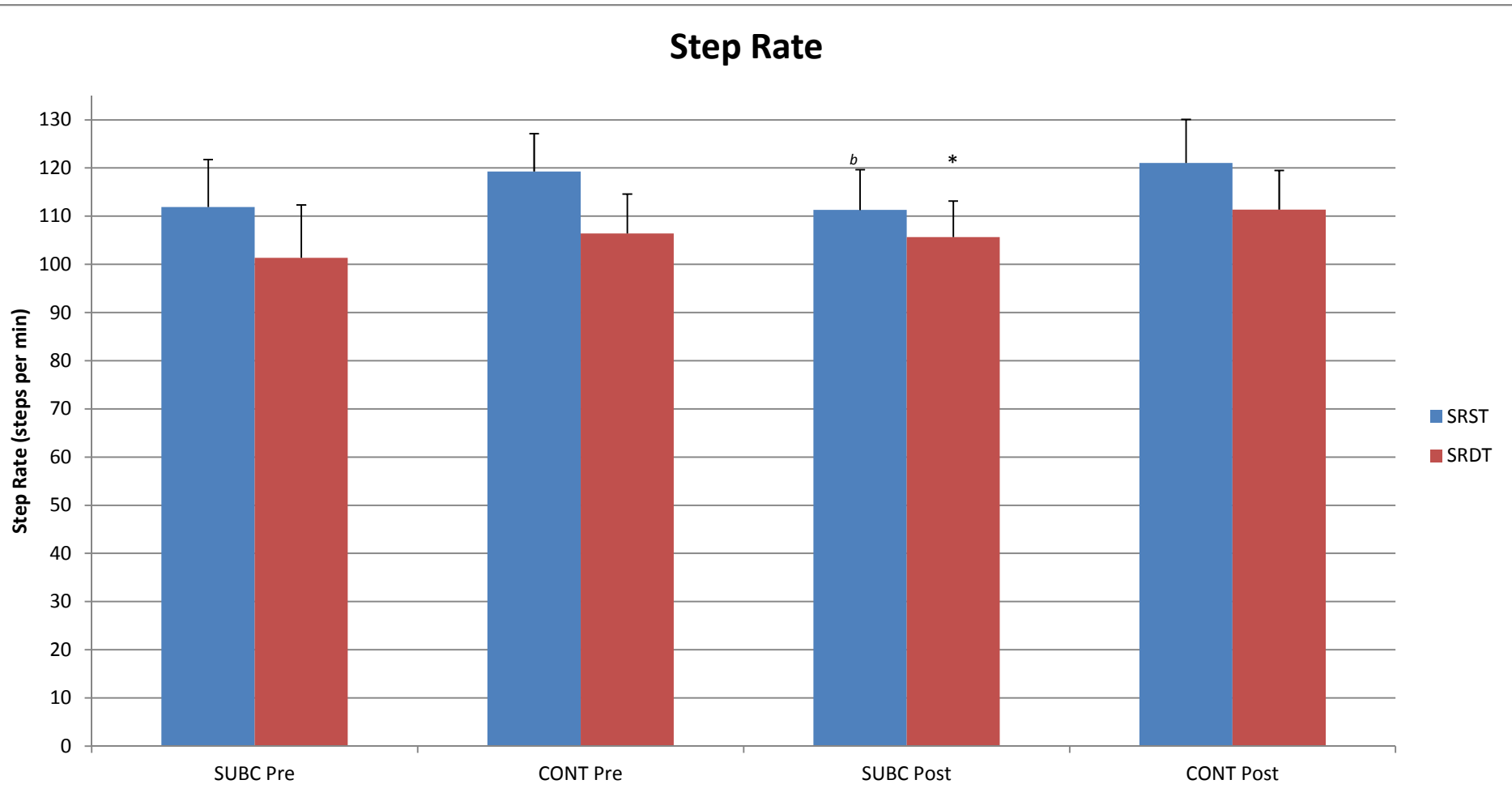


Figure 3. Step rate at preseason (Pre) and postseason (Post); group means \pm standard deviation

^{*}Significantly lower between groups

^bSignificant decrease from preseason to postseason

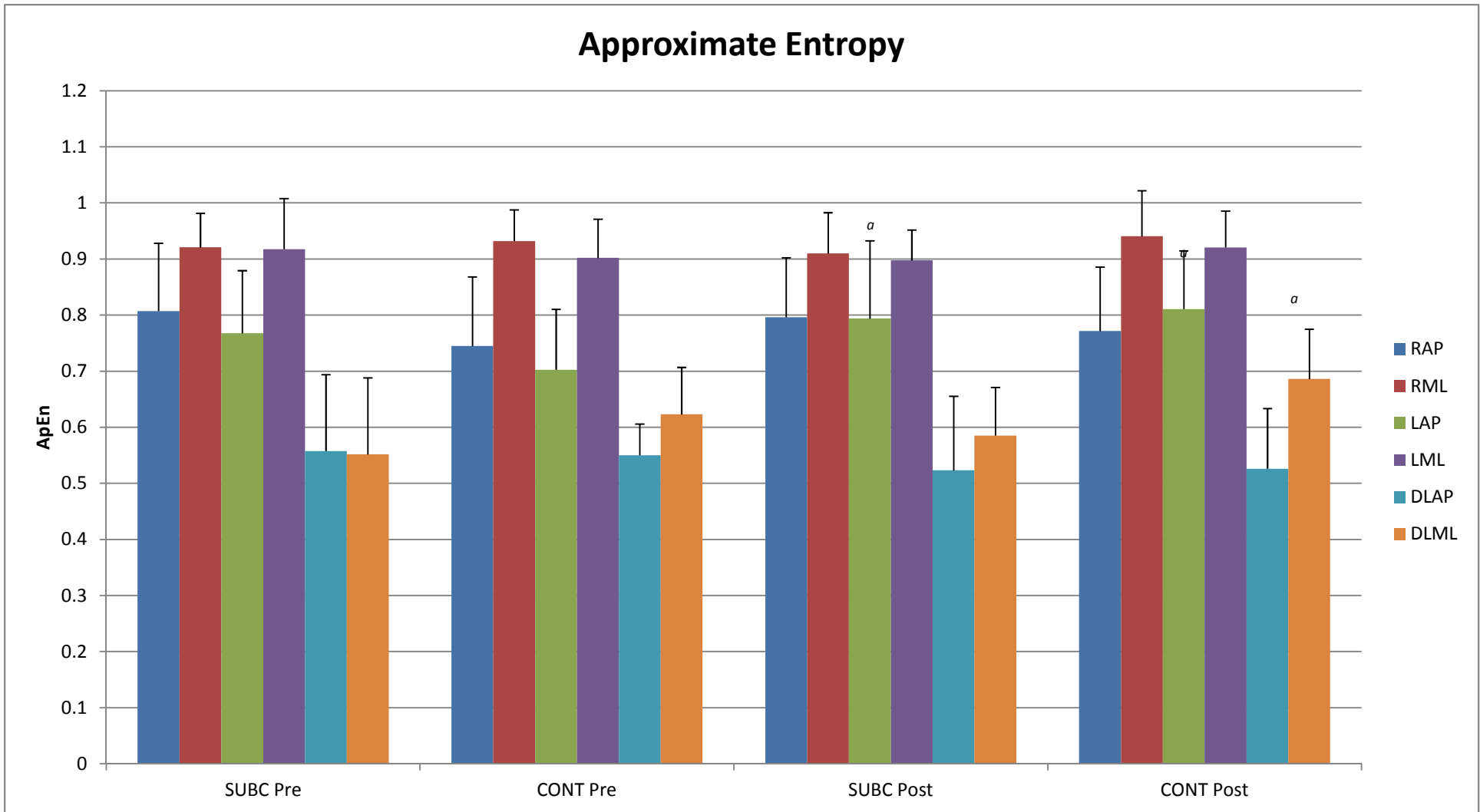


Figure 4. Approximate entropy (ApEn) at preseason (Pre) and postseason (Post); group means \pm standard deviation

^aSignificant increase from preseason to postseason

APPENDIX D

INFORMED CONSENT



**GEORGIA
SOUTHERN
UNIVERSITY**

COLLEGE OF HEALTH & HUMAN SCIENCES

POST OFFICE BOX 8076
STATESBORO, GEORGIA 30460-8076
TELEPHONE (912) 681-0200

CONSENT TO ACT AS A SUBJECT IN AN EXPERIMENTAL STUDY

1. Title of Project: The Effects of Subconcussive Impacts on Postural Stability on Division 1 Football Athletes.

Investigator's Name: Eric Shiflett, ATC, LAT

Phone: (740) 703 – 9058

Participant's Name _____ Date: _____

Data Collection Location: Biomechanics Laboratory, Georgia Southern University Campus

2. We are attempting to describe the influence head impacts which occur while playing football on concussion testing parameters and balance. There will be 80 participants in this study, 40 football players and 40 athletes that sustain minimal impacts to the head. The results of this study will benefit athletic trainers and other health care professionals understand the effects of head impacts on concussion tests.
3. You are being asked to participate in this study because you are a football player who has been assigned a helmet imbedded with sensors which measure the amount and severity of helmet impacts or you are an athlete who does not get hit in the head as part of normal sports activities.

If you agree to participate in this study, you will be asked to attend 2 sessions lasting about 1 hour each over the course of the football season and/or fall semester. During each session, you will be asked to take a brief mental screening test, take a verbal cognition test, and perform a series of balance tests which include walking and balancing on one or both legs.

4. The information we collect on your performance may be sent off campus for analysis, however any information sent will be devoid of identifying characteristics (no one will be able to tell it is you).

5. There is minimal risk associated with participating in this study and it is no greater than your current activities of daily living. You could fall during a balance test; however, a member of the research team will stay in close proximity (e.g., “spot”) you. These are very similar tests to what you do during your pre-participation physicals. You understand that medical care is available in the event of injury resulting from research but that neither financial compensation nor free medical treatment is provided. You also understand that you are not waiving any rights that you may have against the University for injury resulting from negligence of the University or investigators. Should medical care be required, you may contact Health Services at (912) 478 – 5641.
6. You will likely receive no direct benefit for participating in this study, however you will be provided your results, once calculated, if you so request. The results of this study will improve the understanding of head impacts in football and their effect on performance.
7. You understand that all data concerning myself will be kept confidential and available only upon my written request to Eric Shiflett. You understand that any information about my records will be handled in a confidential (private) manner consistent with medical records. A case number will indicate your identity on all records. You will not be specifically mentioned in any publication of research results. However, in unusual cases my research records may be inspected by appropriate government agencies or released to an order from a court of law. All information and research records will be kept for a period of seven years after the termination of this investigation.
8. If you have any questions about this research project, you may call Eric Shiflett at (740) 703-9058. If you have any questions or concerns about your rights as a research participant in this study it should be directed to the IRB Coordinator at the Office of Research Services and Sponsored Programs at (912) 478-0843. This project has been reviewed and approved by the GSU IRB under tracking number H14003.
9. NCAA student-athletes will not receive compensation for your participation in this project. Participants that are not NCAA student-athletes will be compensated \$20 per session. You will be responsible for no additional costs for your participation in this project.
10. You understand that you do not have to participate in this project and your decision to participate is purely voluntary. At any time you can choose to end your participation by telling the primary investigator, Eric Shiflett.
11. You understand that you may terminate participation in this study at anytime without prejudice to future care or any possible reimbursement of expenses, compensation, employment status, and that owing to the scientific nature of the study, the investigator may in his/her absolute discretion terminate the procedures and/or investigation at any time.
12. You understand there is no deception involved in this project.
13. You certify you are 18 years of age or older and you have read the preceding information, or it has been read to you, and understand its contents. Any questions you have regarding the

research have been, and will continue to be, answered by the investigators listed at the beginning of this consent form.

14. You have been provided a copy of this form.

Title of Project: **The Effects of Subconcussive Impacts on Postural Stability on Division 1 Football Athletes.**

Principal Investigator

Eric Shiflett, ATC, LAT
Hanner Building
(740) 703-9058

es03435@georgiasouthern.edu

Other Investigator

Thomas Buckley, Ed.D., ATC
0107-C Hollis Building
(912) 478 – 5268

TBuckley@Georgiasouthern.edu

Other Investigator

Barry Munkasy, Ph.D.
0107-D Hollis Building
(912) 478 – 0985

BMunkasy@Georgiasouthern.edu

Participant Signature

Date

I, the undersigned, verify that the above informed consent procedure has been followed

Investigator Signature

Date

HEALTH HISTORY QUESTIONNAIRE



**GEORGIA
SOUTHERN
UNIVERSITY**

COLLEGE OF HEALTH & HUMAN SCIENCES

POST OFFICE BOX 8076
STATESBORO, GEORGIA 30460-8076
TELEPHONE (912) 681-0200

Please answer the following questions as honestly as possible. Your answers will remain confidential and will **NOT** be shared with your coaches of athletic training staff.

Subject ID _____

Date ____/____/____

Gender: M/F

Year in School: FR SO JR SR 5th

Age: _____

Please answer the following questions about your injury history:

1. Have you ever suffered a concussion? YES NO

If Yes; How many? _____

If Yes; When was your last concussion? _____

2. Have you ever sprained your ankle? YES NO

If Yes; How many? LEFT:____ RIGHT:____

If Yes; how many ankle sprains in the last year? _____

How much time did you miss with your worst ankle sprain _____

Which is your "dominant" ankle? LEFT RIGHT

3. Have you ever broken a bone in your foot or leg? YES NO

If Yes; which bone(s): _____

4. Have you ever hurt you knee? YES NO

If Yes; did you ever tear your meniscus? YES NO

If Yes; did you have surgery? When? _____

If Yes; did you ever tear a ligament? YES NO

If Yes; which ligament, when, surgery?

-
-
5. Have you ever hurt your hip? YES NO

If Yes; please explain: _____

6. Have you ever strained or torn a leg muscle? YES NO

If Yes; please explain: _____

7. Have you injured your low back or had a nerve problem? YES NO

If Yes; please explain: _____

8. Do you have any known balance/metabolic/neurological disorders? YES NO

If Yes; please explain: _____

9. Have you ever been knocked out playing sports? YES NO

If Yes; how many and when?: _____

10. Have you ever been “knocked silly/seen stars” (confused/disoriented?)
while playing sports? YES NO

If Yes; how many times? _____

If Yes; has this happened in the last year? _____

11. Have you ever been hit so hard that you lost your memory while
playing sports? YES NO

If Yes; please explain: _____

12. Have you had any other muscle/bone/joint injuries to your
head, back, legs, or feet? YES NO

If Yes; please explain:

APPENDIX E

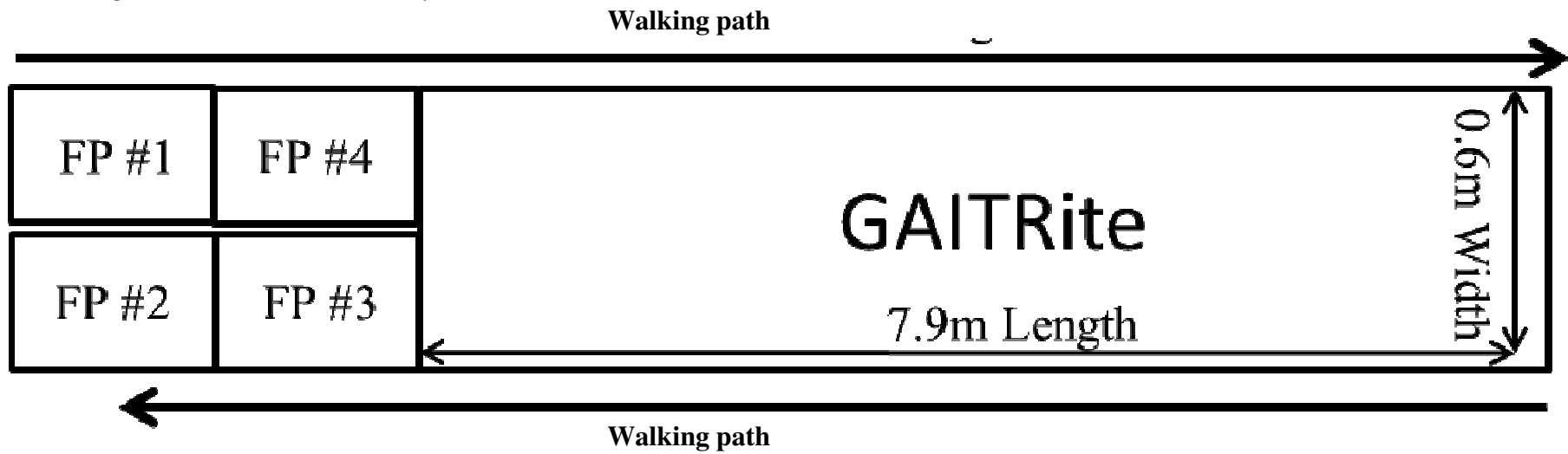
Diagram 1. GAITRite® walkway

Diagram 2. Balance Error Scoring System Stances



Diagram 3. Dual Task Condition Questions and Answers

Name	Cue to Start Walking	Answer
Months of the Year (Reverse Order)	May	May, April, March, February, January, December, November, October, September, August, July, June.
Days of the Week (Reverse Order)	Friday	Friday, Thursday, Wednesday, Tuesday, Monday, Sunday, Saturday.
Serial 7s (Subtract 7 Continuously)	100	100, 93, 86, 79, 72, 65, 58, 51, 44
Five Letter Word (Spell Backwards)	House	E, S, U, O, H
Consecutive Additions ($x - 1 + x$)	4	7, 13, 25, 49, 98

