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The Effect of Repetitive Head Impacts on Postural Control Over the Course of a Single Season

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THE EFFECT OF REPETITIVE HEAD IMPACTS ON POSTURAL CONTROL OVER THE COURSE OF A SINGLE SEASON

by

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(Under the Direction of Nicholas Murray)

ABSTRACT

INTRODUCTION: Repetitive head impacts (RHI) have been shown to have detrimental effect on cognitive function, as well brain activation patters as seen with fMRI.[1-3] While the effects of RHI on neurocognitive function have been well established, the physical effects of RHI on an athlete's postural control have undergone limited investigation.[2-4] **PURPOSE:** To investigate the effect of RHI on postural control, both static and dynamic, in NCAA Division I athletes over the course of a single season. **METHODS:** Eighteen NCAA Division I were recruited from a single university, nine football athletes as the experimental or contact group (CON), and nine NCAA baseball players as the non-contact control group (NON). Subjects' postural control, measured via a force platform, was tested before and after their fall season using a static and dynamic postural control assessment. The static postural control assessment consisted of eyes open (EO) and eyes closed (EC) quiet standing, while the dynamic postural control assessment consisted of the Wii Fit Soccer Heading Game (WiiSoccer). Center of Pressure data was used to quantify 95% confidence ellipse (CE), peak excursion velocity (PEV) in the medial-lateral (ML) and anterior-posterior (AP) direction, and sample entropy (SampEn) in the ML and AP direction. **RESULTS:** Repeated measures ANOVA's revealed significant differences (p=0.027) in EO SampEn ML between pre (CON: 0.53, NON: 0.58) and post-season testing (CON: 0.42, NON: 0.53). In addition, there was significant differences (p= 0.001) between pre (CON: 0.68, NON: 0.52) and post-season (CON: 0.57, NON: 0.50) in EO SampEn AP; the CON group also displayed a significantly greater (p=0.018) decrease in SampEn AP than the NON group. There was a significant effect (p=0.009) of time by group in EO CE; the CON group had a significantly greater increase between pre (0.37 mm) and post-season (0.49 mm) compared to the NON group (0.34 vs. 0.30 respectively). **CONCLUSION**: These results suggest that athletic participation does influence static postural control, and that exposure to RHI may contribute to postural instability. Significant changes were only found in a static environment, but were detected using linear and non-linear variables.

INDEX WORDS: Postural control, Repetitive head impacts, Sub-concussive impacts, Balance

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DEDICATION

I dedicate this project to my family, friends and loved ones, without whom completing this project would not have been possible. To my mother, Laura, thank you for your support and guidance throughout this endeavor; your level headedness steered me through the worst of it, and your utter confidence drove me through the many sleepless nights of work. To my father, David, thank you for all of your academic advice, and thank you for all the hikes you took me on. To my brother, Brian, thank you for your reassurance during my transition into graduate school and not getting too angry when I didn't return your calls. To James, words cannot express how thankful I am to have your constant love and support, thank you for your encouragement and patience these past two years. Finally, I dedicate this work to Ms. Bobbi Southard, without your mentorship and backing I would not have discovered Athletic Training, and would be lost in a tiresome and monotonous career, and for that I am forever grateful.

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CHAPTER 1: INTRODUCTION

CHAPTER 1.1 EPIDEMIOLOGY

In 1998, the Center for Disease Control reported that an estimated 300,000 sport-related concussions (SRC) occur in the United States annually;[5] However, this projection severely under-reported SRC rates. The 1998 report excluded all concussions that did not involve loss of consciousness, and only included individuals who sought medical attention through a hospital or emergency room.[5] It is now understood that only 6.9 - 8.3% of SRC involve loss of consciousness, and the majority of SRC are not sent to the hospital or emergency room.[6,7] More recent projections, which accounts for these shortcomings, estimates that 1.6 - 3.8 million SRC's occur annually.[5] Football can account for as much as 47% of all SRC due to the high participation rate, and high contact nature of the sport.[8]

CHAPTER 1.2 REPETITIVE HEAD IMPACTS

Repetitive head impacts (RHI) are defined as multiple blows to the head or body that do not meet the criteria for the clinical diagnosis of a concussion in respects that they do not elicit symptoms that warrant the diagnosis of a concussion.[9,10] Despite the lack of symptoms reported following exposure to RHI, it is hypothesized that long term exposure may have behavioral, neurological, and physical consequences.[1,10] In previous research athletes who sustained a higher frequency of impacts to the top and front of the head during a football season had significantly decreased activation of the dorsolateral prefrontal cortex (DLPFC) during fMRI examination.[3,11] The decreased activation mirrored that of athlete's with a diagnosed concussion despite no manifestation of symptoms.[3,11]In addition, it was investigated if these decreases in activation of the DLPFC resulted in decreased neurocognitive performance, as was observed in the concussed athletes.[2,3]

The DLPFC is the area of the brain responsible for storage, manipulation and utilization of feedback information called working memory, as well as the preparation of actions and decisions.[12] As a result the athletes exposed to RHI performed significantly poorer on computerized neurocognitive testing, specifically in areas of recognition, and recall. Overall, athletes experienced functional and anatomical changes within their brain that mirror a concussive injury, despite showing no outward signs or symptoms of a concussion.[2,3] As such, symptom reporting may not be a reliable tool to determine or detect detrimental changes within the brain that occur with RHI.

Postural control assessments and neurocognitive assessments have been used in hopes of providing a more objective diagnostic tool compared to symptom reporting, which is the most prominently used assessment tool.[13-16] Postural control assessments test the central nervous system's ability to integrate and coordinate multiple sensory inputs into an effective motor output. Maintaining postural stability requires a high degree of integration between the somatosensory, vestibular and visual system[17]. The integration system must then process this sensory data to decide an appropriate motor response.[17] As such, postural stability is a task that requires a high degree of neurocognitive function, and is highly affected by SRC.[18,19] Since it has been observed that exposure to RHI results in the degradation of neurocognitive function similar to SRC and previous research has noted a relationship between poor neurocognitive performance and postural control, RHI may result in a postural instability similar to SRC.[20]

Only one previous investigation was found that examined how RHI affected postural control. The study investigated the correlation between impact frequency and changes in postural control over the course of a single season.[21] There was no correlation found between any RHI measurements, including frequency and cumulative impact burden, and changes in postural control, specifically using the Sensory Organization Test (SOT). Changes were noted, however, in the Balance Error Scoring System (BESS), as a result of RHI. Static stances, such as the BESS and Rhomberg have been shown to be specific in identifying concussive injuries, but only up to 5 days post initial injury.[22] In this instance static postural control is defined as the ability to maintain the body is a fixed posture through the appropriate orientation of center of mass over the base of support, through the use of reactionary movements.[23] Past five days the injured players' scores returns to baseline, and their postural control appeared to recover. However, more sensitive tools, such as a force plates, detected postural control deficits up to 30 days post-injury in the same athletes.[24-26] The SOT, which utilizes force plate data, has been shown to be a more sensitive measure that can detect subtler deficits longitudinally. However, both the SOT and the BESS are strict static postural control tasks, which have been shown to be less sensitive at detecting deficits past 10 days post-injury compared to dynamic postural control tasks.[14,27]

Dynamic postural control is defined as the ability to transfer COP around the base of support, while the body is in motion.[23] Dynamic postural control assessments have been shown to be more effective at detecting postural changes while a concussed athlete appears to be symptom free, as compared to static postural assessments.[28-30] Traditional static assessments attempt to isolate specific systems of postural control, such as the visual, vestibular or somatosensory system and test the systems ability to react to external perturbations. However, such assessments like the BESS fail to test the convergence and outputs of multiple systems, and may not tax patients to their full limit of stability.[31] Dynamic assessments require anticipatory movements in order to avoid an obstacle, or hit a target as well as reactionary movements in order to adjust to changing surroundings and to correct errors. The Wii Fit Soccer Heading Game (WiiSoccer), which is an environmentally relevant dynamic task, has been shown to be an effective tool to assess a concussed individual's posture.[30,32] The WiiSoccer requires participants to shift their weight from left to right in order to dodge obstacles and hit targets, creating a goal-oriented sport-like task.[30] The WiiSoccer requires the participant to process their visual surrounding and integrate information regarding obstacles and targets in order to make an appropriate decision (weather to move toward or away from an object). Due to this additional requirement of cognitive processing, the WiiSoccer unlocks degrees of freedom which are otherwise easily reduced during static postural control assessments due to the simplicity of the task. By creating a sufficient cognitive load, the WiiSoccer may be able to detect subtle changes that occur throughout an athletic season compared to more rudimentary static stance assessments.

CHAPTER 1.4 LONG TERM EFFECTS

Evidence is continuing to appear regarding the tie between long term exposure to RHI and neurological degeneration, including chronic traumatic encephalopathy (CTE).[33-36] Studies of retired professional football players have revealed cerebral atrophy, and diffuse axonal injury.[35-37] These anatomical changes within the brain have been coupled with behavioral changes, and decreased executive function, as well as parkinsonism and motor neuron disease.[38,39] While the extent of the relationship between these diseases and RHI are still emerging it is imperative for research to begin to understand the acute effects of RHI to understand the magnitude of impact it plays on an athlete's physical function.

STATEMENT OF PURPOSE

The purpose of this study was to study the effects of RHI on postural control, both static and dynamic, in NCAA Division I athletes over the course of a single season.

CHAPTER 2: METHODS

CHAPTER 2.1 SUBJECTS

Twenty-six male Division I NCAA athletes were recruited from a single institution, 13 football players who were the experimental group (CON) and 13 baseball players who were the non-contact control group (NON). Baseball was chosen as the control group due to their minimal risk for RHI, as well as to control for comparing athletes to non-athletes. The 13 members of the CON group as well as the NON group consisted of a variety of positions (See Table 1: Position demographics of CON and NON groups).

Table 1: Position demographics of the CON and NON groups

CON Positions	**n=13**
Running back	2
Linebacker	1
Defensive back	2
Offensive Line	4
NON Positions	**n=13**
Pitcher	6
Catcher	2
In-Fielder	2
Out-Fielder	3

Subjects were excluded for select neurological, cognitive, and behavioral disorders that may have affected postural control. (See Table 2: Exclusion criteria for postural control testing). In addition, any subject who sustained a diagnosed concussion during the season was automatically excluded from this study. Subjects who were being withheld from participation or presented with an altered gait due to lower extremity injury were also excluded from the study.

Table 2: Exclusion Criteria for Postural Control Testing

Diagnosed Attention Deficit/ Attention Deficit Hyperactivity Disorder, or Learning Disabilities	Lower extremity injury limiting participation in sport or altering gait during the time of testing
Diagnosed depression, or anxiety	Lower extremity surgery within the past 6 months
Any history of a diagnosed concussion	Disorders of the inner ear
Neurological Disorders causing altered or loss of sensation in lower extremities	Balance Disorders, such as vertigo, stroke, and labyrinthitis

Of the 26 subjects, 7 subjects (4 CON; 3 NON) were excluded from the study due to concussive injury or history of concussion. One NON subject was randomly selected to be excluded from data analysis to maintain an equal number of subjects between each group. Age, height, and weight of all subjects were reported during the first testing sessions (See Table 3: Demographics of CON and NON subjects following exclusion of subjects with concussive history).

Table 3: Demographics of CON and NON subjects following exclusion of subjects with concussive history

	NON (n=9)	**CON (n=9)**
Age (yrs.)	20.4 ± 1.6	19.7 ± 1.1
Height (cm.)	184.7 ± 4.6	183.1 ± 3.3
Weight (kg.)	81.1 ± 29.0	81.8 ± 5.4
Time Between Testing (days)	94 ± 44.29	121.33 ± 53.70

CHAPTER 2.2 INSTRUMENTATION

During the postural control assessment a 40 x 60 cm force platform (1000 Hz, AMTI model OR-6, Watertown, MA, USA) was used to measure 95% Confidence Ellipse (CE), peak excursion velocity (PEV) in the anterior-posterior (AP) and medial-lateral direction (ML), and Sample Entropy (SampEn) AP/ML. These variables were chosen to obtain both linear force plate variables (CE and PEV) and non-linear force plate variables (SampEn). Raw acceleration and position data was collected and processed via Vicon Nexus 1.8.5 (Vicon, Denver, CO). CE measures the area of sway during a time series by encompassing 95% of all collected COP points into an ellipse, and the ellipse is measured in mm. Therefore, lower values indicate lower amounts of sway, while higher values indicate greater magnitudes of sway within the time series. PEV was used to assess the sensory input and phasic neuromuscular control of the postural control system.[40] Finally, SampEn was used to assess the neuronal organization of the postural control series. SampEn quantifies the regularity of a COP time series by calculating a value between 0 and 2, with lower values indicating a more inflexible pattern and higher values indicating high irregularity.

For dynamic postural control assessment, the Wii Fit Soccer Heading Game (WiiSoccer) was used. The WiiSoccer offers a sport relevant goal-oriented task in which the subject must move a virtual avatar left and right in order hit targets (soccer balls) and avoid obstacles (cleats and panda heads). Subjects were rewarded through a point system in which they received points by hitting targets and had points subtracted for hitting obstacles. The WiiSoccer lasts for approximately 60 s with a total of 80 soccer balls appearing on the screen.

Each subject in the CON group was fitted with a Riddell Speed Classic helmet (medium, large, or extra-large sized; Riddell Corp. Elyria, OH) prior to the start of the season. To quantify the CON group’s cumulative impact burden (CIB) subject’s helmets were then instrumented with a HIT system accelerometer unit. Data was gathered during every game, practice, and scrimmage. Helmet sensor units were checked each week for proper function, and battery charge level.

The HIT System is a side-line reporting system that has the ability to record the frequency, location and magnitude of impacts sustained in football players; the helmet unit consists of 6 single-axis accelerometers and a signal transducer embedded within the helmet (See Figure 1).[41-43] Impacts with a magnitude greater than 10 g are registered on any one of the six accelerometers are recorded then sent to a laptop located on the sideline with a signal receiver. Impacts are recorded for 40 ms. Recorded impacts consist of 12 ms pre-trigger and 23 ms post.[44] Within the helmet unit, there is a data storage device that can store up to 100 impacts in the event the controller loses contact with or is out of range of the signal receiver. Data is presented in 4 different windows on the sideline computer: the first displays a vector with the impact location, the second is an acceleration vs. time graph of impacts, the third displays peak acceleration magnitude history, and the final displays the impact location history. If peak linear impact magnitudes are registered at above 98 g an alert is sent to a clinician on the sideline via a pager.

Figure 1: Head Impact Telemetry (HIT) System Helmet Accelerometer Unit. The HIT System helmet unit consists of 6 single-axis accelerometers which are denoted by the red circles seen on the right. The helmet unit records and reports peak linear acceleration of impacts to the helmet to side line computer system.

In a single study, the HIT System's accuracy of the linear acceleration measures reported have been found to be accurate when comparing linear accelerations measured in Hybrid III (H-III) anthropomorphic crash dummies.[43] The HIT system was found to overestimate the resultant linear acceleration by only 0.9%, compared to underestimating rotational acceleration by 6.1%.[43]

The HIT System was used to calculate cumulative impact burden (CIB), number of sessions, as well as average impact magnitude. Original RHI research used the HIT System to determine CIB of subjects. Originally CIB was determined by counting the total number of impacts of each participant. Impact frequencies simply take the number of times an athlete sustained an impact, without regard for the impact magnitude, or peak linear acceleration. As such, using frequency to determine CIB may be less descriptive, because it fails to take the magnitude of the impact into account. CIB can also be quantified by totaling the peak linear accelerations of each impact, for each athlete, thereby considering impact magnitude. Therefore in this study, CIB (See Figure 2: Calculation of Cumulative Impact Burden) was quantified in the CON group, by totaling the recorded linear acceleration magnitudes of each subject over the course of the entire fall season. Impact frequency was simply a count of each recorded impact. Impact magnitudes were determined through average impact magnitude (AIM) (See Figure 3: Calculation of Average Impact Magnitude), in which the recorded peak linear acceleration was averaged for each subject.

$$\text{CIB}= \sum_{\text{g}=1}^{n} x_g$$

Figure 2: Calculation of Cumulative Impact Burden, n= number of recorded peak linear accelerations, x_g = magnitude of recorded peak linear accelerations (g)

$$\text{AIM}= \frac{1}{n}\left(\sum_{g=1}^{n} x_g\right)$$

Figure 3: Calculation of Average Impact Magnitude, n= number of recorded peak linear accelerations, x_g= magnitude of recorded peak linear accelerations (g)

CHAPTER 2.3 PROCEDURES

Subjects recruited were volunteers from a single university. Subjects who participated in baseball were classified in the control group (NON); while those who participated in football were classified in the experimental group (CON). Subjects signed an informed consent document that was approved by the institutional review board prior to testing. Subjects also completed a health history questionnaire at each time point to determine inclusion or exclusion of the study.

Each subject was tested at two time points, the first was prior to participation in practices or games (PRE), the second following the completion of the fall season (POST). At both time points (PRE and POST). The postural control assessment included: 1) Static stance eyes open (EO), 2) static stance eyes closed (EC), 3) WiiFit Soccer Heading Game. Static postural control tasks (EO and EC) were administered in a randomized order, where as WiiSoccer was performed as the final task to eliminate any affects it may have played on the static stance assessments. For all postural control tasks, the Wii Balance Board (WBB) (Nintendo Corporation, Redmond, WA, USA) was placed on top of an AMTI force plate (50Hz, Watertown, MA, USE, OR6-6) then zeroed out, and the WBB calibrated to their weight. Subjects were asked to stand barefoot on the WBB, which was approximately 140 cm away from a 127 x 127 cm projection screen.

Static stance postural assessments were conducted using a quiet stance in which subjects stood with their feet together (malleolus to malleolus). Subjects were instructed to stand in the center of the WBB with their hands in a comfortable and still position. Subjects were told to look at a specific fixed point (point five) on the projection screen in front of them during the eyes open trials, and to remain as still as possible throughout the trial. (See Figure 4a. – 4b.) Each trial of quiet stance lasted 30 s, and each condition was performed 3 times. The tester instructed subjects when to begin quiet stance and when to relax.

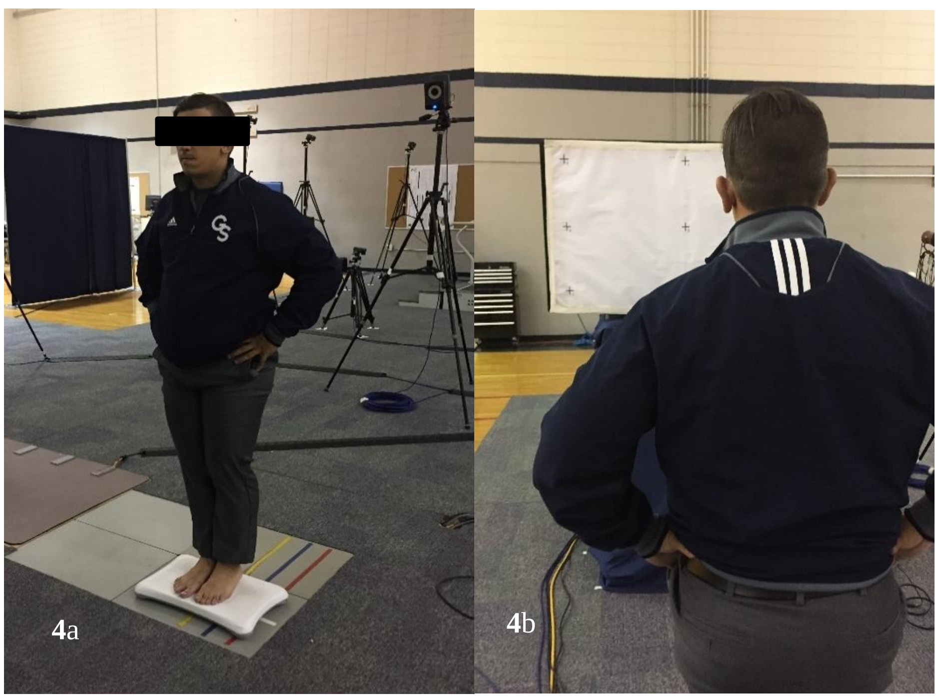

Figure 4: Static postural control assessment. 4a) Position of subject for eyes open and eyes closed condition, 4b) Subject asked to look at point 5 in the middle of the projection screen during the eyes open condition

Dynamic postural control of each subject was measured via the WiiSoccer. Subjects were then instructed that the WBB did not register upper body motion; in order for the Wii Avatar to move from side-to-side, they had to keep their knees slightly bent and initiate all motion from the hips, ankles and knees rather than the torso or head. (See Figure 5) Subjects were allowed a single practice round to acclimate themselves to the task. The practice round was then followed by 2 trials of data collection. The same testing procedures and instructions were provided during POST testing as the PRE testing.

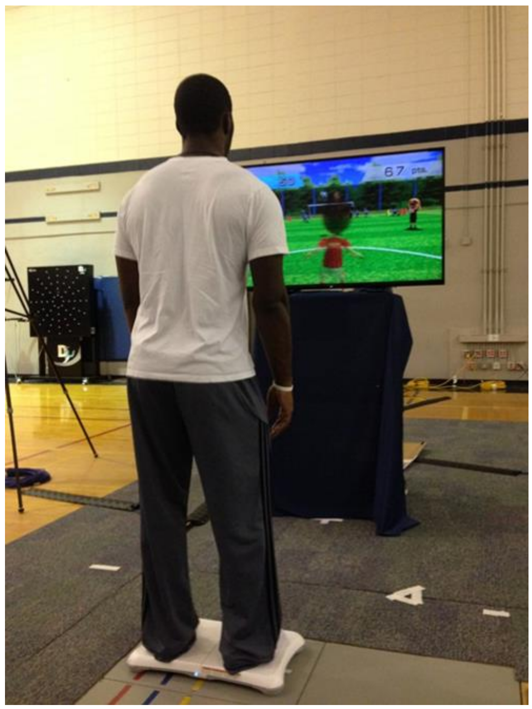

Figure 5: Subject using the Wii Balance Board (WBB) and Wii Fit Soccer Heading Game, in playing position

CHAPTER 2.4 DATA ANALYSIS

Age, height, weight, and time between testing periods were analyzed using an independent samples t-test. COP data was processed through a custom code in MATLAB (2010, MathWorks Inc., Natick MA, USA) using a 4^{th} order Butterworth low pass filter with a 10 Hz cutoff. COP data was analyzed for normality using skewness and kurtosis. Skewness and Kurtosis of each COP variable were analyzed to assess normality of distribution. COP data was then analyzed via fifteen 2 groups (CON; NON) x 2 time (PRE, POST) points repeated measures ANOVA in SPSS. To control for multiple comparisons, as well as reduce the chance of type I error due to low sample size a Holm-Bonferroni correction was applied, and alpha level was set at p= 0.003. Between subjects' comparisons assessed the change between CON and NON COP data. Within subject comparisons were also used to assess change between PRE and POST. By performing a repeated measures ANOVA, it is assumed that variances are equal among each population, scores among subjects are equally and normally distributed, and there is sphericity of the covariance. Further analysis of each variable was done via a two-tailed paired samples t-test. Descriptive statistics of impacts including CIB, and AIM were calculated, then used to quantify the number and severity of impacts sustained by the CON group. All statistical analyses were performed in Statistical Package for the Social Science® v.21 (SPSS) (IBM, Armonk, NY, USA)

CHAPTER 3: RESULTS

CHAPTER 3.1 DEMOGRAPHICS

An independent sample t-test was used to analyze the age, height, weight, and number of days between testing points of the remaining 18 subjects. There was no statistical difference found between age, height, and weight of the subjects (See Table 4: Subject Demographics of Contact and Non-Contact Athletes). In addition, there was no significance difference in time between testing points of each group (See Table 4). Subjects in the CON group experienced a CIB of 1,234 g ± 10,098 g and AIM of 30.7 g ± 6.8 g over the course of 52 practice sessions and 19 game/scrimmage sessions The number of impact recorded across all CON subjects was 2,207, 204 (9.2%) of which were over 90 g.

CHAPTER 3.2 POSTURAL CONTROL ASSESSMENTS

Repeated measures ANOVAs revealed a significant ($F(1,22) = 23.311$, $p=0.001$, $\eta= 0.987$) difference in EO SampEn AP in PRE and POST testing of NON and CON. In addition, there was a significant effect ($F(1,22) = 8.854$, $p=0.018$, $\eta= 7.41$) of group on EO SampEn AP. Following a paired sample t-test it was observed that CON EO SampEn AP significantly ($p= 0.029$) decreased between PRE and POST, whereas there was no statistical difference ($p=0.241$) between NON's PRE and POST EO SampEn AP. The CON group showed a greater decrease in SampEn AP between PRE (0.675 ± 0.138) and POST (0.571 ± 0.120) testing, compared to the NON's group PRE (0.532 ± 0.083) and POST (0.501 ± 0.120) (See Table 4 and Figure 6).

Table 4: EO Sample Entropy AP in NON and CON groups shown for both PRE and POST testing

	Pre	**Post**
NON	0.52 ± 0.08	0.50 ± 0.12
CON	0.68 ± 0.14	0.57 ± 0.12

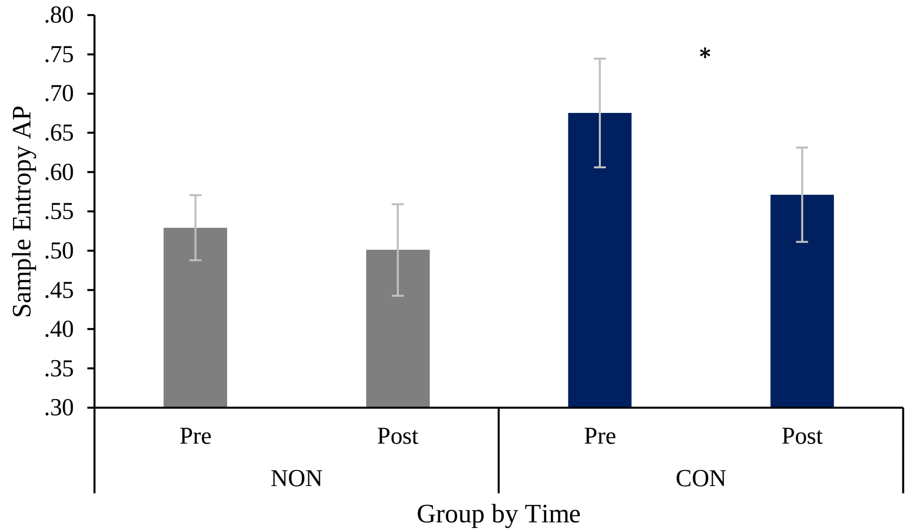

Figure 6: Comparison of Pre and Post testing between both NON and CON groups for EO Sample Entropy in the AP direction. * = p< 0.003

Finally, in the EO condition repeated measure ANOVA's revealed no significance for group effects of PEV AP (p= 0.182), PEV ML (p= 0.198), CE (p=0.009), or SampEnML (p=0.027). In addition, no significance was found for effects of time for PEV AP (p= 0.219) or PEV ML (p= 0.793).

Repeated measures ANOVA's revealed no significant effect of time in the EC condition for the following variables: PEV AP (p= 0.911), PEV ML (p=0.234), CE (p= 0.500), SampEn ML (p= 0.925), and SampEn AP (p= 0.338). There was also no significant effect of group in the EC condition for the following variables: PEV AP (p= 0.344), PEV ML (p= 0.239), CE (p=0.028), SampEn ML (p=0.891), and SampEn AP (p= 0.163).

Finally, no significant effect between groups was observed in the WiiSoccer condition for the following variables: PEV AP (p= 0.575), PEV ML (p=0.910), and CE (p= 0.228), SampEn ML (p= 0.990), and SampEn AP (p= 0.544). There was also no significant effect of time on the

WiiSoccer condition for the following variables: PEV AP (p= 0.431), PEV ML (p= 0.318), CE (p= 0.905), SampEn ML (p=0.899), and SampEn AP (p= 0.417).

CHAPTER 4: DISCUSSION

4.1 REVIEW OF THE PURPOSE

The purpose of this study was to investigate and quantify the effects of RHI on postural control, both static and dynamic, in NCAA Division I athletes over the course of a single season. RHI was defined as an impact that does not meet the criteria for clinical diagnosis of a concussion by failing to produce symptoms associated with concussion, but is hypothesized to have potential negative long-term effects when occurring over a long period of time.[9,10] It was hypothesized that there would be no significant changes in static postural assessment in either group, CON or NON, between PRE and POST testing. It was also hypothesized there would be significant change in both group in the dynamic postural control assessment in SampEn, but no significant changes would be observed in linear measures (CE and PEV). Finally, the CON group would experience significantly greater decreases in SampEn compared to the NON group

4.2 REVIEW OF THE RESULTS

Our hypotheses regarding changes in postural control being evident in dynamic rather than static postural control tasks were not met. The only significance found out of all three conditions, EO, EC and WiiSoccer, was in the EO condition; contradictory to previous concussion research, which found dynamic and dual task conditions to be more effective at detecting changes in postural control compared to static stance.[27,28,45] Similar to previous studies that utilized dual task, the WiiSoccer task was able to unlock the subject's degrees of freedom. It was observed that all subject's excursion, confidence ellipse, and entropic values increased compared to the static stance assessments. Therefore the changes in postural stability between the static and dynamic assessment were consistent with dual tasks performed in previous research.[45]

Previous research has found that when performing novel tasks subjects undergo, greater amounts of postural sway as well as increased sway velocities, due to underdeveloped and less robust neural networks compared to those of a familiar task.[19] Consequent to a decreased amount of available neural networks, subjects also have an increase in regularity (lower entropic values) compared to tasks in which they are highly familiar with.[46] In addition, research has shown that postural stability in novel tasks can improve over the course of multiple trials and sessions, as the robustness of the neural networks increases, and motor patterns are learned.[47] However, the WiiSoccer testing sessions performed in this study were not long enough nor were they close enough together to elicit the learning effect that previous research has observed.[47] Finally, high levels of athletic ability have been shown to decrease sway velocity and increase variability, but by having subjects perform a task that was unrelated to their specific sport (baseball or football) the advantage of athletic ability was eliminated.[46] Consequently, the WiiSoccer was a novel task that may have elicited postural instability in all subjects.

A significant decrease was observed in EO SampEn AP in both groups between PRE and POST. Specifically, the CON group had a greater decrease in EO SampEN AP than the NON group. A decline in entropic values indicate an increase in movement regularity.[48] Like any neural network, the postural control system has multiple neural pathways that can be used to accomplish the same task. A higher entropic value (closer to 2) indicates a lower variability of neural networks being used, thus creating a less variable and confined movement pattern.[48] Conversely, the lower the entropic value (closer to 0), the more neural networks are being utilized resulting in a more variable movement pattern. Healthy subjects exist in the middle of these two extremes; too high of an entropic value can indicate postural instability due to high amounts of noise within the system, indicating multiple neuronal pathways being utilized and an inability to reduce degrees of freedom to produce an efficient motor task. A low entropic value indicates a successful reduction of degrees of freedom, however it also indicates a system that is inflexible and uses a very consistent neuronal pathway, which may make subjects more susceptible to external perturbations. This may be the result of axonal injury and indicate the inability for neural networks to conduct appropriately.[48] Previous RHI research has shown the alteration and degradation of white matter in the brain, as well as decreased activation after being exposed to RHI.[11,49] Therefore, it is possible that diffuse axonal injury or a decrease in conduction velocity of the postural control system's neural network attributed to the decline of the CON group's entropic values.

The decreases in entropic values observed in the CON are consistent with previous concussion research, which has also observed decreases in entropic values following a concussive injury.[48,50] Much of previous concussion research has utilized approximate entropy rather than sample entropy.[48,50] While the two variables are similar, approximate entropy has been shown to be less reliable than sample entropy in shorter data sets.[51] Previous research has shown healthy stable surface athletes, such as baseball and football players, to have approximate entropy values at approximately 0.6 in the AP direction in an EO condition.[52] The PRE testing SampEn AP values in this study were identical to previous literature with an average of 0.6. In addition, previous concussion research using approximate entropy observed a decline of approximately 0.1 in the AP direction.[48] The results found in this study were similar in regards to the AP direction, observing a decrease in SampEn of approximately 0.1 in the CON group who was exposed to RHI, and a decrease of 0.02 in the NON group. The CON group displayed a similar decrease in AP entropic values as compared to athlete's who had sustained a concussion.

As stated previously, RHI research has not utilized entropic values, and postural control assessments used have been limited to the sensory organization test (SOT) and Balance Error Scoring System (BESS).[4] Previous research found that changes within the SOT had no correlation with RHI, but the BESS was negatively affected by higher CIB.[21] However, both the SOT and the BESS may be flawed assessment's to test postural control changes due to RHI.

The SOT utilizes force plate variables to assess static postural control, however it's assessment is limited in both variables used and nature of reported results.[53] The SOT is a series of six 20 s trials consisting of 3 different visual scenarios (eyes open, eye closed, and referenced visuals surround); these visual scenarios are also paired with two different surface conditions (fixed and sway reference) [53] The SOT then uses the COP data collected to report one equilibrium score that reflects how the subject performed over the course of all of the trials, therefore eliminating the ability to compare different scenarios such as eyes open and eye closed.[14] Additionally, the SOT only reports AP displacement velocity, as shown by this study there were no significant changes in EO or EC PEV, however significant changes were seen using non-linear force plate variables which can not be reported via the SOT. Linear measures quantify the deviations and magnitude of movement away from the center of mass within the base of support. Conversely, approximate and sample entropy assess the variability of patterns of movement and how often they are repeated. By looking at the quality of postural control rather than then magnitude of movement it, entropy been shown to be a more sensitive measure in detecting changes in of postural control compared to linear measures, which is consistent with the findings of this study.[48,52,54-56]

Like any research, this project is not immune to limitations. The largest limitation of this study is a limited sample size. While the convenient sample was small conservative statistical analysis was used via the Holm-Bonferoni correction of the alpha value to mitigate Type I error. During the time of testing the CON group was participating in their fall competitive regular season, while the NON group was participating in their non-traditional fall ball season. As such, training intensities and loads were likely different between the two groups and fatigue due to training cannot be ruled out as a confounding factor. Finally, it was not possible to measure or quantify the AIM or CIB in the NON group due to lack of available technology, therefore it must be assumed that the NON group was honest on the health history questionnaire regarding the number of impacts sustained to the head and that their exposure was minimal.

CHAPTER 4.3 CONCLUSIONS

In conclusion by utilizing a static stance assessment coupled with nonlinear measures we were able to detect significant changes in the EO condition between our CON group and NON group. Significant decreases in CON SampEn AP may be attributed to exposure of subjects to RHI and an increase in the regularity of utilized neural networks. These decreases mirror the effects concussive injury plays on entropic values. By utilizing nonlinear force plate variable significant changes in the CON group were observed between PRE and POST, which were not observed in previous literature due to the use of linear variables. Future research may be able to utilize this variable to track postural control changes over the course of multiple seasons, as well as better understand the role RHI plays into the changes of postural control. This research would be paramount in linking the effects long-term exposure to RHI and SRC to the degradation in the postural control system.[35,38] Said research may begin to define the relationship between RHI and consequences that occur later in life including CTE, behavioral changes, and cognitive decline.

APPENDIX A

LIMITATIONS

1. The results of this study cannot be generalizable since the subject pool is limited to a single university.
2. Small amount of subjects may increase the chance of type I error.
3. Training intensity may have been different in the experimental vs. control group due to in-season vs. out-of-season training.
4. RHI in the control group cannot be measured due to lack of available technology.
5. Subjects in the contact group are limited to only those who play football since technology is not yet available to record impact in other non-helmeted contact sports.
6. The results of this study cannot be generalizable to the female population since testing is limited to only male sports.
7. Testing is limited to those athletes without a history of concussion and are free of lower extremity injuries, therefore results cannot be generalized to a population other than healthy athletes

DELIMITATIONS

1. The population that was tested was limited to Division I athletes from a single university.
2. Subjects who were included had to be in relatively good health with no history of neurological injury within the 6 months and free of lower extremity injury at the time of testing.
3. Controlling for gender variances by testing only a single gender group.
4. Controlling for the effects of training on postural control by utilizing athletes as a control group.
5. Controlling for variances between athletes and non-athletes by using an athletic population as the control group.

ASSUMPTIONS

The following items are assumed within this study:

1. Subjects are honest on the health history questionnaire to properly screen and exclude potential subjects.
2. Subjects will try their best on both static and dynamic tests for all trials.
3. Subjects within the CON group will wear the HIT System helmet unit for all practices, scrimmages, and games.
4. Subjects within the CON group will not alter the HIT System helmet unit in any way throughout the study.
5. Subjects within the NON group had limited exposure to repetitive head impacts.

RESEARCH QUESTIONS

It is the aim of the current study to investigate the following research questions:

1. Does postural control change over the course of a single season?

2. Is there a difference in postural control changes between contact athletes and a set of control non-contact athletes?

3. Is there a difference in postural control changes between static and dynamic posture assessments?

4. Are non-linear measures of postural control (Sample Entropy) a better measure of change compared to linear measures (95% confidence ellipse, peak excursion velocity)?

HYPOTHESIS

Based on previous research we hypothesized that there would be no significant changes in static stance assessments between PRE and POST in either group with linear or nonlinear measures. Additionally, it was hypothesized that there would be a significant change in dynamic postural control in both groups, assessed through the WiiSoccer. It was also hypothesized that the CON group would have a significant decrease in postural stability compared to the NON group in non-linear measures (SampEn); specifically the CON group would have a significantly great decline in SampEn compared to the NON group. Finally, no significant changes would be seen using linear measures (PEV and CE) in WiiSoccer.

APPENDIX B: REVIEW OF LITERATURE

INTRODUCTION

In the past 5 years research has shifted its focus from the effects of a single high magnitude impact to the effects of multiple less severe impacts. The neurocognitive effects of repetitive head impacts (RHI) have been well investigated, however the effects on postural control have only been investigated in a single study.[11,21,49] While this study found no significant relationship between RHI and postural control further studies are needed using more sensitive assessments and variables. It is the purpose of this literature review to review current postural control assessments in concussion and RHI literature, and to determine the best possible postural assessment to observe postural control in conjunction with RHI.

EPIDEMIOLOGY

In 1998, the Center for Disease Control reported that an estimated 300,000 sport-related concussions (SRC) occur in the United States annually.[5] However, this report severely under-reported the rate of SRC. The 1998 projection only includes individuals who received care from a hospital or emergency room; [5] additionally, this projection only included cases where the individual lost consciousness.[5] The 300,000 excludes individuals who did not seek medical attention, sought other sources of medical attention (such as an outpatient clinic or military facility). Finally the majority of SRC's were misdiagnosed because the patient did not lose consciousness.[5] It is now understood that only 6.9% - 8.3% of all SRC's result in LOC.[6,7] A patient does not have to lose consciousness in order to sustain a concussion, however there is a persisting assumption that loss of consciousness is the most important diagnostic factor of concussions.[57]

More recent projections have taken into consideration the number of athletes who are cared for by health care professionals outside of the hospital setting and acknowledges the fact that concussion does not always result in a LOC. The lack of a standardized definition of concussion has created considerable dilemmas with the reporting, documentation, and education of concussions. While there are several definitions of concussion, the most widely used definition is a brain injury defined by complex pathophysiological process affecting the brain, induced by biomechanical forces.[58] This pathophysiological process may be the result of a direct or indirect blow, which results in short-lived neurological impairment and may result in clinical changes.[58] Most epidemiological studies have used this definition or a similar variation to investigate incident rates of SRC.

The majority of SRC epidemiological studies conducted have observed only football, due to the high-risk and high contact nature of the sport. Additionally, football has the highest number of subjects in both high school and collegiate athletics providing a large pool of subjects to select from.[59,60]

Incidence rate ratio (IRR) has been the most commonly used way to calculate injury rates in athletics. IRR's utilizes athlete-exposures, participation in either a game or practice, to observe injury frequency. IRR's are calculated by dividing the number of concussions by the number of athlete exposures (number of practices or games participated in).[7,8] In 2011 an IRR of 5.58 concussions per 100,000 persons was reported in athletic populations.[61] Comparably, in 1998 the CDC observed 3.41 injuries per 100,000 lay-persons.[61] Reasons for this increase in injury rate may be due increased interest in concussion rates ensuring proper documentation. CDC projections from 1998 may under-report documented concussions due to clinicians using non-specific internal classification of disease codes. [62] Furthermore, the CDC reports on concussions and sport related-concussions as one entity. It is possible that athletes are at a higher risk for concussion compared to the average sedentary individual due to increased exposure rates. A recent study observing collegiate football reported an IRR of 3.74/1,000 A-E which was only superseded by wrestling and ice hockey; all of which are above the IRR for the general public reported by the CDC. [63,64]

Another method of reporting concussion incidence rates is injury rates which compare the number of concussions to the number of total injuries sustained by a sample. Shankar et. al. (2007) reported that 11% of all injuries reported, in both collegiate and high school football, were concussions.[65] Annually, football accounts for the highest percentage of concussions out of any other sport; as much as 47% of all SRC occur when participating in football. [8] In 2007, in an effort to reduce head injuries, the NCAA introduced rules to limit the amount of contact practice hours, discourage initiating contact with the head or crown of the head and to eliminate the targeting of an opponent’s head during tackling. Despite rule changes studies have consistently observed a higher concussion IRR in competition compared to practices.[8,63,64,66] With the number of subjects in athletics continuing to increase the concern is that the number of sports-related concussions will also continue to rise.[59,67]

It is the recommendation of the NCAA for clinicians to use a multifaceted approach during the assessment and diagnosis of a concussion. These multifaceted approaches commonly include a symptom checklist, neurocognitive evaluation, and postural control evaluation.[15] Symptom reporting is one of the most heavily relied upon evaluation tools when assessing a concussion, despite the fact that symptom reporting is highly subjective and has severe underreporting issues. The chief complaints among concussed athletes include headache, dizziness, and confusion.[68] It is reported that over 60% of all SRC experience some form of postural instability of some form. Along with experiencing symptoms of postural instability 30% of SRC have measurable postural control deficits using postural control assessments. [22,27] Computerized neurocognitive evaluations have found cognitive impairments in 62% of athletes who have a SRC, indicating deficits in concentration, memory, and attention.[69] It has been observed that the recovery of postural control and cognition lag behind the resolution of symptoms post-concussion.[22] As such it is important to understand the changes and recovery that occur in postural control and cognition with head impacts.

PHYSIOLOGY OF POSTURAL CONTROL

Postural control has been a commonly used clinical diagnostic tool for concussions. [24,53] Postural stability is defined as the body's ability to maintain the center of gravity, or the "horizontal projection of the body", within the body's base of support[48,53] Maintaining postural stability can be thought of as a closed-loop system, where the body's movement is constantly monitored and assessed. In this system, a desired body position is established as a reference mechanism, multiple sensory systems then provide continuous sampling information known as feedback. This feedback is then compared to the reference mechanism to determine the amount of error between the actual and desired body position.[70] This process requires the central nervous system (CNS) to integrate sensory afferent information, and process information through stimuli recognition and response selection; as such, postural control is not only a physical task but one that requires cognitive integration.[70] As previously stated, the level of error is constantly monitored by an executive level, typically the cerebral cortex. If the level of error becomes significant then the executive level will exert a corrective signal to muscular systems.[70]

Sensory information from the environment is received from the somatosensory, vestibular and visual system.[53] The visual system plays the largest role in maintaining postural control. [71] The visual system, like the previous systems discussed, consists of an afferent and efferent system.[71] The afferent system specializes in perceiving object motion and recognition through central vision, and motion perception through peripheral vision.[71] While central vision obtains sensory information regarding the body's surroundings and positioning of environmental stimuli, the peripheral vision is used to incorporate how the body and objects are moving through space. In static quiet standing it has been shown that the visual system can over-ride the information provided by the vestibular or somatosensory system.[70] The visual system also provides spatial information for more dynamic task, such as playing sports, in order for individuals to anticipate and intercept moving targets.[70]

The somatosensory system consists of peripheral sensory receptors including Golgi tendon organs (GTO), muscle spindles (MS), and joint receptors. Both GTO's and MS's relay information regarding muscle length and tension, while joint receptors relay information about joint angle and pressure. The sensory information is sent through the dorsal root of the spinal cord and to interneurons within the spinal cord.[70] In the case of repetitive motions, such as walking and quiet stance, it is theorized that the brain stem is able to produce simple motor outputs through central pattern generators (CPG) with minimal input from the cerebral cortex.[72] Specifically CPG's alternately stimulate the flexors and extensors of a joint creating small oscillations. While CPG's may be able to produce repetitive motions without the inclusion of the brain they are limited in the amount of disturbances they can control for.[56,73] According to the uncontrolled manifold hypothesis, CPG's are able to control for perturbations within certain parameters, but once these perturbations extend past the CPG's ability the cerebral cortex must intervene to provide a different motor output.[56]

Finally, the vestibular system consists of 3 semicircular canals which can detect rotational and linear accelerations by movement of fluid, known as endolymph, within the canals. [74] Information gathered via the semicircular canals is transmitted to the cerebrum via the vestibulocochlear nerve which travels to the cerebellum and pons.[74] The cerebellum plays a key role in the integration of sensory information into appropriate motor outputs. [75] The cerebellum utilizes input from the vestibular system to coordinate proper limb adjustment and movement via the vestibulospinal reflex.[74] The vestibular and visual system work closely with each other to allow the body to maintain a central gaze despite movement of the head, this is known as the vestibular ocular reflex.[53,76]

Proper integration of all three systems allows humans to maintain proper postural control. Key components of the integration of sensory input, as well as the planning and organizing movement in goal-oriented tasks is short-term and working memory.[12] Working memory is the process of active maintenance of information regarding environmental stimuli, whereas short term memory is the ability to learn, recall and recognize cueing. The dorsolateral prefrontal cortex (DLPFC) plays a key role in working memory as well as short-term memory, therefore a key component to the preparation and planning of motor tasks. If a single sensory system provides faulty information, or if the integral system of the brain sustains an injury, such as concussion, individuals experience postural instability.

PATHOPHYSIOLOGY AND NEUROPHYSIOLOGY OF CONCUSSIVE INJURIES

Concussion is characterized by five major pathophysiological consequences: ionic flux, hyper-glycolysis, changes in cerebral blood flow, energy deficit, and reduction of conduction velocity. Following a force applied to the head or surrounding body axonal cell membranes are disrupted or damaged which can cause increased mechanoporation, or cell membrane ionic leakage, as well as the release of glutamate.[77,78] Accelerations can be linear or rotational in nature; linear acceleration is the result of an impact in a singular radial direction, whereas rotational acceleration is the result of a tangential force causing both linear and rotational movement of the brain.[79] As a result of rotational acceleration, shearing forces are placed on the brain, causing deformation of the axons, also known as diffuse axonal injury.[80,81]

Diffuse axonal injury (DAI) increases the mechanoporation, or permeability of axons, and ultimately results in the release of glutamate, which triggers the opening of ion channels.[82] The opening of ion channels allows sodium to flood into axonal cells, and potassium to escape.[77,83-85] The consequential efflux of potassium, results in dispersed and rapid depolarization of axons. Following the depolarization, an axon's ability to fire is suppressed due to a refractory period, at which time the cell normalizes the amount of potassium within the cell via sodium-potassium pumps. Normal refractory periods in healthy brains are localized to specific areas of the brain in which axons were fired. In concussed individuals the firing of axons is wide-spread throughout the brain, due to DAI.[80] This wide-spread firing leads to a suppression of axons throughout the brain, also known as spreading depression. [85-87] A consequence of the *spreading depression* is a disruption in timing and conduction of neuronal signals.[88] Overall these deficits decrease the brain centers ability to communicate with each other, physically these deficits manifest themselves in symptoms such as fogginess, confusion, attentional problems, and headaches.[88]

As a result of increased ion flux sodium-potassium pumps are sent into overdrive to correct the membrane potential, which consequently increases glucose and ATP utilization. As such anaerobic metabolism becomes the primary fuel pathway, which in turn causes lactic acid production to increase. In healthy individuals cerebral blood reduces the amount of lactic acid accumulation and provides oxygen to the brain to promote aerobic metabolism.[82,83] however it has been observed in rat models that traumatic brain injury resulted in a marked decrease in cerebral blood flow, not only to the affected area but to the brain as a whole.[32] The reduction of blood flow to the brain only exacerbates the metabolic imbalance within the brain by diminishing the amount of waste and lactic acid removal, as well as reducing the amount of oxygen available to the brain for aerobic production of ATP.

It has been observed that metabolic and conduction deficits can last 7-10 days in animal models.[86] This reduced metabolism leaves the brain in an energy crisis, where energy supply can no longer meet demands. This energy crisis can lead to longer lasting impairments of the brain.[89] These longer lasting impairments can predispose individuals to repeat concussion, and may increase the brain's sensitivity to biomechanical forces.[6]

ASSESSMENTS OF POSTURAL CONTROL

The BESS is a series of 3 testing positions that is performed on two different surfaces, stable and unstable. The testing positions consist of double leg stance, non-dominant single-leg stance, and tandem stance with the non-dominant leg as the back foot. During each position the subject is asked to keep their hands on their hips and eyes closed for 20 sec. Each error that a subject makes is recorded by a tester. Errors consist of: lifting their hands off their hips, opening their eyes, stumbling or falling out of the testing position, abduction or flexion of the hip past 30°, or remaining out of the testing position for longer than 5 sec. The maximum number of errors for each test is 10, lending a maximum score of 60. The BESS has shown to be specific when assessing postural control changes in concussed players (specificity of 0.98). However, the BESS's sensitivity is limited in respects that scores typically return to baseline values by 7 days post-injury. It has been observed that concussed athletes continue to have postural changes past 7 days as shown by the SOT, an instrumented postural control assessment.[47,50] The BESS is an assessment that is reliant on the tester's scoring and therefore completely subjective. The intra-rater reliability of the BESS can range from 0.55 to 0.98 when looking at the individual stances, and .57 to .85 when looking at the total BESS score. The BESS has shown to be sensitive in detecting gross postural control deficits, but may not be an appropriate tool to use to assess subtler postural control deficits or as criteria for return to play.

The SOT is a series of six 20-second trials consisting of 3 different visual scenarios (eyes open, eyes closed, and referenced visual surround); these visual scenarios are paired with two different surface conditions (fixed and sway reference).[24] The prerogative of the SOT is to tax or provide conflicting information to the postural control system, in order to isolate each component of system (somatosensory, vestibular, and visual). The subject's postural control is observing through changes in center of pressure (COP), which are recorded via force plate.[41,42,43] Center of pressure can be defined as a sensorimotor response to external perturbations which result in a point of pressure applied to a surface in order to maintain a body's center of mass (COM) within a base of support.[52,54,90] The SOT measures the range and maximum displacement of COP, or the distance traveled, in the anterior-posterior (A-P) direction.[48] The SOT then uses the COP displacement data to report an equilibrium score showing how a subject did over the course of all trials.[53] The SOT is a more taxing balance assessment compared to the BESS because it requires subjects to produce a proper reaction in the presence of false sensory input. Unlike the BESS the SOT is an objective assessment of postural control by utilizing force plate data; however, the SOT does not utilize any measurements in the medial-lateral (M-L) direction, and relies solely on linear COP measures (displacement), rather than non-linear measurements such as entropy.

The postural control system is arranged in a hierarchy of structures; the highest of which is the cerebral cortex which processes and conceptualizing information from multiple systems, and is concerned with coordinating and decision making of motor outputs.[53] The 2nd level of the hierarchy is responsible for the integration of sensory information and coordination of efferent signals to the muscles as a response.[53] This level consists of the cerebellum, sensorimotor cortex, and brain stem.[53] The 3rd and final level is the spinal cord which consists of sensory and motor neurons; these neurons receive direction from the 2nd level structures.[53] As discussed previously the body may be able to maintain static and repetitive motions through CPG's and with little involvement of the cerebral cortex.[72] Consequently static assessments that only require reflexive movements, such as the BESS and SOT, may only tax the postural control system up to the mid-level of the hierarchy. In order the thoroughly test all levels of the postural control system, an assessment must elicit disturbances outside of the CPG's capability and require input from the cerebral cortex. By neglecting the cerebral cortex in postural assessment, it is difficult to assess the system's ability to incorporate information from multiple systems, which is essential in the dynamic setting of sport participation.

Dynamic and dual-task postural assessments have been shown to be more sensitive to subtle postural control changes in COP as compared to static stance assessments.[29,91,92] Dynamic postural assessments require the subject to anticipate, and plan movements compared to static assessments, which only require reflexive movements. Dual-task places a cognitive load on the system to act as a distractor from a motor task, such as walking. It is possible that dual-task and dynamic assessments test a higher level of the postural control system than static stance.

Catena et. al investigated the effects of dual-task walking, and obstacle crossing (a dynamic assessment) on gait in concussed athletes.[92] The dual-task required athletes to perform a question and answer task while walking down an instrumented walk way. Dual-task compared to single-task walking elicited higher M-L sway, and a larger separation between COM and COP, both of which indicate a more unstable gait.[92] Obstacle crossing required the athletes to step over a small hurdle while trying to maintain a natural gait velocity. During obstacle crossing concussed individuals adopted a more conservative gait strategy by decreasing their gait velocity as compared to single-task walking, they also increased the clearance of the trailing foot over the obstacle compared to healthy controls.[92]

The Wii Balance Board (WBB) and Wii Fit Soccer Heading Game (WiiSoccer) has also been shown to be an effective dynamic assessment of posture in a concussed population.[30] WiiSoccer is a virtual reality, sport-specific game which requires subjects to move a virtual character left and right in order to hit targets and avoid obstacles. The WiiSoccer game requires subjects to integrate incoming sensory information and decide the appropriate motor response, whether it be to move the character out of the way of an obstacle or move them to hit a target. To move the avatar left and right subjects must shift their weight in the M-L direction appropriately. COP data (velocity, excursion values, and sample entropy) is collected via a force plate, which is underneath the WBB, during the game. Murray et. al. (Ahead of print) used WiiSoccer, WBB and force plate data to assess postural control in concussed athletes and compared it to healthy sedentary controls. [30] The concussed group of athletes continued to have difference in medial-lateral and anterior-posterior peak COP velocities, even 15 days after injury when compared to healthy controls, which may indicate greater instability.[30]

Previous studies have utilized linear measures (in both A-P and M-L directions) provided by force plate data to define postural control deficits.[21,30,41] Linear measures consider the deviations and magnitude of movement of center of mass (CoM) within the base of support. Linear measures consist of COP displacement, excursion, and accelerations in both the M-L and A-P direction. However, it has been shown that non-linear measures, such as approximate entropy (ApEn) and sample entropy (SampEn), are a more sensitive measure in detecting changes in the characteristics of postural control compared to linear measures.[48,52,54-56] Traditional linear models view variance and deviations of movement as an error, or indication of postural instability. Conversely, the dynamical systems theory considers complex movement patterns to be an indication of a more flexible postural control system, in other words the motor control system is able to adapt to multiple perturbations using varying pathways.[55] Entropy observes the likelihood that patterns of movement remain similar throughout the trial, or observing the nature of an individual's movement rather than simply the magnitude of movement in linear measures.[55]

MEASURING IMPACTS

A large area of research over the past decade has been the biomechanical forces contributing to concussions, specifically linear and rotational accelerations in collegiate and high school players. Accelerations have been measured via the Head Impact Telemetry (HIT).[41,42] The HIT System is a side-line reporting system that has the ability to record the frequency, location and magnitude of impacts sustained in football players; the helmet unit consists of 6 single-axis accelerometers embedded within the helmet.[41-43] The 6 accelerometers maintain contact with the head to measure accelerations of the head rather than that of the helmet.[44] Impacts are recorded when they have a peak linear acceleration greater than 10 g , the minimum threshold of the. Data of the impact is collected for 40 ms total at 1,000 Hz. Twelve milliseconds of data are recorded pre-trigger, and 23 ms are recorded post-trigger, to ensure that the full impact is collected.[44] Impact data is then sent via a signal transducer to a receiver and laptop on the sideline where data is displayed in real time.[44] Within the helmet unit there is a data storage device that can store up to 100 impacts in the event the controller loses contact with or is out of range of the signal receiver.[93] Data is presented in 4 different windows on the sideline computer: the first displays a vector with the impact location, the second is an acceleration vs. time graph of impacts, the third displays peak acceleration magnitude history, and the final displays the impact location history.[44] If peak linear impact magnitudes are registered at above 98 g an alert is sent to a clinician on the sideline via a pager.

There is limited research on the validation of the HIT System and the accuracy of impact accelerations recorded. In a single study the HIT System's measurements of linear acceleration measures were found to be accurate when compared to accelerations measured in Hybrid III (H-III) anthropomorphic crash dummies.[43] The H-III dummies contain accelerometers within the head mold's center of gravity in order to maintain a theoretical acceleration of the brain rather than of the skull.[94] The H-III dummies were fit with a medium-sized helmet, both with and without the helmet sensors, and were then struck using a linear impactor.[43] The HIT system was found to overestimate the resultant linear acceleration by only 0.9%, compared to underestimating rotational acceleration by 6.1%.[43] Linear acceleration and rotational acceleration were not significantly different from each other alone ($p=.88$).[43] However, when combined with the probability of concussion linear acceleration was a significantly ($p<.015$) better predictor compared to rotational accelerations.[43]

Several studies have attempted to establish a biomechanical profile of concussions, observing of both linear and rotational acceleration. The first attempts to uncover this concussion threshold began with the National Football League's mild Traumatic Brain Injury Committee.[95] The committee issued a series of studies utilizing game footage to analyze location of impacts, linear acceleration, and head change velocity in professional football players.

Linear acceleration was determined through the use of game film provided by the NFL. Relative velocity of the players was determined by using yard line hashes to determine change in distance over time. The major finding of this series was that concussion-resulting impacts had a peak linear acceleration of 98g, compared to 60g of peak acceleration in non-concussive impacts.[95] Concussed players received impacts at an average speed of 9.3 ± 1.9 m/s, and a head velocity change of 7.2 ± 1.8 m/s compared to 5.0 ± 1.1 m/s in un-concussed players ($p<.005$).[95] This study was the foundation for the establishment of the 98 g linear acceleration alert threshold with the HIT system. There were several limitations to this study that would bring the validity of the study to question. First, only 26 concussion-resulting impacts and 6 non-concussive impacts were analyzed to establish thresholds.[95] Second, the method of reconstructing hits had a large margin for error, video analysis was used to establish relative velocity and change in velocity. The videos used were of poor quality. There was also a very large standard deviation for linear acceleration thresholds, for players receiving a concussive impact (98 g) had a standard deviation of 28 g, and players receiving non-concussive impacts (60 g) had a standard deviation of 24 g.[95] With such great variances it is difficult to say that reported thresholds are definitive and reliable.

Thus, researchers sought to test the reliability of this reported “concussion threshold.” Guskiewicz et. al. (2007) recorded 104,714 impacts of 88 collegiate football players, 13 of which resulted in a concussion.[41] Concussive peak linear acceleration (PLA) ranged from 60.51 g to 168.71 g, the average PLA of concussive impacts was 102.8 g. The PLA showed no significant correlation with clinical outcome measures, including postural control, neurocognitive, and symptom scoring assessments. Similar results were found when comparing peak rotational acceleration and clinical outcome measures ($p>.05$).[41]

Broglio et. al. (2011) conducted a similar study investigating impact magnitudes of concussed high school football players and their relationship to changes in neurocognitive (NC) performance.[69] Researchers assessed several variables in relation to NC performance changes, including time of impact in relationship to start of activity, time from previous impact, peak linear acceleration, and peak rotational acceleration. The average PLA for concussed athletes was 93.6 g, and players on average experienced 25 impacts before receiving a concussive blow. There were no significant relationships found in over 100 correlation tests assessing the relationship between subjects' impact data and NC performance changes.[69] Broglio et. al. (2011) and Guskiewicz et. al. (2007) demonstrated that there is little correlation between the severity of the impact magnitude and the resulting cognitive or physical impairment in athletes.[41,69]

McCaffrey et. al. (2007) used a similar study design that observed recorded impact magnitudes in collegiate football players, and resulting impairments on clinical outcome measures[42] Subjects were dichotomized into two groups: players who had received an impact above 90 g, and players who had not received an impact above 60 g; both groups used athletes who had not been formally diagnosed with a concussion. There was no significant relationship found between linear acceleration and postural control when comparing to baseline scores ($p=.799$).[42] Interestingly, players who had received a linear acceleration of over 90 g actually performed better in aspects of NC testing including math processing ($p<.001$), and procedural reaction time $p<.001$).[42] However, the number of symptoms reported was statistically greater after high magnitude impacts compared to baseline ($p<.001$), but the total symptom severity score had no significant difference among test groups (low: $p=.858$, high: $p=.120$).[42]

While this study demonstrated that the severity of impact did not affect postural control, the number of symptoms, while they were apparently reported as mild, did increase in players who had received high-magnitude impacts. Both McCaffrey et. al. (2007) and Guskiewicz et. al. (2007) rejected the theory of a 98 g linear acceleration concussion threshold.[41,42] Both studies demonstrated that football players are either remained symptom free when receiving impacts well above the 98 g threshold, or received a concussion when experiencing impacts well below the threshold. The "concussion threshold" is more likely to be a combination of multiple factors that contribute to the overall concussion risk, rather than one single variable that induces injury.

REPETITIVE HEAD IMPACTS AND CLINICAL OUTCOMES

In the past 5 years, research has shifted its view from studying the effects of a single high magnitude impact to the effects of multiple less severe repetitive head impact (RHI). As discussed previously, it was believed a linear acceleration threshold of 98g resulted in a 75% injury risk, but was disproven through several studies.[41,42,69,93] In one of these studies, Guskiewicz et. al. (2007), it was noted that one player received a concussion following a 63.85g impact, well below the threshold.[41] This particular player had received two relatively large impacts earlier in the day, during morning practice, and another large hit immediately prior to the concussive hit.[41] This observation brings rise to the theory of cumulative effects of impacts, and how they contribute to injury.

While the HIT System provides the ability to collect data regarding RHI no standard has been set on how to report or handle said data.[96] Various techniques have been used to report data including: total linear accelerations (also known as cumulative impact burden), total rotational accelerations, HIT severity profile (HITsp)(a weighted analysis that considers rotational acceleration, impact location and impact duration), frequency and total linear accelerations above 90 g.[21,96,97] The most common measure that has been used is the frequency or number of impacts that occur over the course of a single season. [11,21,49] However, frequency may not be descriptive enough to depict the actual burden of individual players which has a large variability in nature.

Breedlove et. al. (2012) investigated the relationship between the number of impacts high school football players sustained and changes in neurocognitive examinations.[49] An fMRI baseline examination was administered to high school football athletes during pre-season. Players were monitored throughout the season using the HIT system, two players who had not been diagnosed with a concussion were recruited each week for a follow up fMRI examination. One of the two players was from the top 50% of number of impacts sustained, and the other was a player from the bottom 50% of number of impact. All players invited for follow-up examination had reported to be symptom-free. Upon neurocognitive examination, a select group of players were found to have either significantly lower verbal or visual composite scores, despite reporting no symptoms. The same group of subjects sustained the majority of their blows to the top-front region of the helmet, especially impacts that were above 80 g than any other group of subjects..[49]

Similar to previous research, this study demonstrates that it is not simply one variable that induces injuries, but a combination of multiple factors such as location, magnitude, previous history, and age. It is also illuminates the issue that symptom reporting may not be sensitive enough to detect minute changes within brain function, but can only detect gross impairments. Symptom reporting has been shown to have a large under-reporting issue in athletics, despite this fact it is the most relied on assessment for clinical diagnosis of concussion.

A continuation of Breedlove et. al. (2012) was conducted by Talavage et. al. (2014), which investigated how the neurophysiological changes within the brain affected cognitive function.[11] The ImPACT® was used to assess neurocognitive function and fMRI was used to assess neurophysiological function. Four players were found to have changes in the activation of the dorsolateral prefrontal cortex, throughout the course of the season.[11] Surprisingly the activation pattern was similar to that of the concussed group rather than the healthy controls, despite reporting to be symptom free. These players also had statistically significant reductions in either verbal or visual memory.[11] Similar to Breedlove et. al. (2012), the players who experienced these changes in ImPACT and fMRI had a higher number of total impacts, and experienced more impacts greater than 80 g to the top front of the helmet.[11] This study further demonstrated that the changes found on fMRI's in asymptomatic players may manifest themselves in subtle cognitive impairments.

While the effects of RHI on neurocognitive (NC) performance have been well investigated, the effect of RHI on physical measures, such as posture, has not been as thoroughly researched. The Sensory Organization Test (SOT) and Balance Error Scoring System (BESS) have been used previously to assess postural control in relation to RHI in collegiate athletes pre- and post- season.[21] In this study, linear regressions were used to compare the change scores (pre-season minus post-season score) of the SOT and BESS to impact data, determining frequency of impacts, frequency of impacts over 90g, and cumulative impact burden.[21] In this study there were no relationships found between impact data and change scores in the SOT, but in the BESS cumulative impact burden (CIB) was a significant predictor of a worse performance. [21] As discussed previously the BESS's sensitivity is limited to gross postural control deficits, and may not be sensitive enough to detect subtle changes in posture that may exist. Similarly, the SOT is limited due to the use of only linear force plate measures (A-P displacement). A dynamic or dual-task assessment of athletes pre- and post-season has yet to be observed. These dynamic measures in conjunction with non-linear force plate variables, such as sample entropy, may be able to observe changes that were otherwise unseen.

LONG TERM IMPLICATIONS OF RHI

The long-term implications of exposure RHI are of concern. It has been hypothesized that exposure to repetitive subconcussive impacts over the course of a long period may increase a player's risk of developing cognitive dysfunction later in life, such as Alzheimer's, depression, and Parkinson-like motor dysfunction. [33,98] Thirty-five percent of professional –football players were found to have some form of cognitive impairment at an uncharacteristically young age.[33]

Several studies attribute these cognitive declines to chronic traumatic encephalopathy, or CTE. CTE reportedly is a neurodegeneration which is characterized by widespread presence of hyper-phosphorylated tau protein, which also features atrophy of the cerebral cortex.[34] Along with the previously mentioned cognitive declines, CTE is characterized clinically by behavioral symptoms of irritability, aggression, heightened suicidal ideology, anxiety and paranoia.[34,35] At this time there is no way to directly link the exposure of RHI and presence of CTE due to the degeneration developing of multiple decades.

CONCLUSION

The construct of postural control in relation to repetitive head impacts has been explored, but with no significant findings.[21] Changes to the brain as a result of repetitive head impacts have been identified as subtle changes that may not be detectable by traditional clinical measures, such as static stance assessment.[11,49] The previous study observing RHI and postural control changes used the BESS as an assessment tool, which has been show as an insensitive measure outside of acute concussion recovery.[22,53] The same study also utilized the SOT which excludes M-L data, and relies on linear measures (displacement). The WBB, along with non-linear force plate data, has been shown to be a sensitive functional measures that can detect changes in postural control up to 15 days post-injury. [30] Therefore, the purpose of this study was to assess postural control changes over the course of a season in both contact and non-contact sports, by using a dynamic postural assessment (WiiSoccer) as well as a static assessment, utilizing non-linear force plate variables.

APPENDIX C

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: Identification of Persistent Impairments in Postural Control Following Concussion

   Investigator's Name: Nicholas Murray, Ph.D. Phone: (912) 478 - 0203

   Participant's Name: ______________________________ Date: ______________________

   Data Collection Location: Biomechanics Laboratory, Georgia Southern University Campus

2. We are attempting to compare the balance, coordination and bodily control of individuals who have suffered a concussion and compare that to people who have not suffered a concussion. There will be 500 participants in this study, about half whom and half who have not suffered a concussion. The results of this study will help athletic trainers in the evaluation, treatment, and return to play decision making process in individuals who have suffered a concussion.

3. You are being invited to participate in this study because you have recently suffered a concussion or are a control subject. Additionally, you have no history of any nerve, inner ear or balance disorders, metabolic disorders, or significant injury to the lower extremity.

   If you agree to participate in this study you will be asked to attend testing sessions lasting 25 min. You will be tested post-concussion, your return to play day and then every 7 days over the next 2 months. During the session you will be asked to both stand still, on 2 feet and 1 foot, walk at normal pace while solving mental challenges and play the Wii Soccer game. During the session you will stand and walk across force platforms and a carpet which measures the forces you create on the ground. You will also stand on a Wii balance board that is on top of a force platform and wear a headset. Finally, we will record your performance on the balance, cognitive, and neuropsychological testing, and your self-reported symptoms that you complete as part of your normal post-concussion assessment. The balance test will be video recorded.

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's you). The video recordings will not be sent off-campus.

5. Your performance during these tasks will be compared to your performance during your baseline test, if you performed one, when you began playing sports at Georgia Southern University.

6. The risk assumed during the testing is no greater than you experience during your normal daily activities. There is minimal risk of physical injury or mental discomfort while performing this experiment. There is a risk of falling during the gait and balance trials; therefore, a member of the research team will be in close proximity should you lose balance. The headset you will be wearing

for the Wii Soccer game does not your impair vision and should sit comfortably on your head like a ball cap. If the headset becomes uncomfortable at any time, a member of the research team will immediately remove it. 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.

7. 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 may be used to better understand and treat individuals who have suffered concussions.

8. You will attend testing sessions over the next 2 months lasting about 25 min.

9. You understand that all data concerning yourself will be kept confidential and available only upon your written request to Nicholas Murray, Ph.D. You understand that any information about your records will be handled in a confidential (private) manner consistent with medical records. Your identity on all records will be indicated by a case number. You will not be specifically mentioned in any publication of research results. However, in unusual cases your 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 5 years after the termination of this investigation. The video recordings will be retained for seven years as required by the Georgia Board of Regents policy.

10. If you have any questions about this research project, you may call Nicholas Murray at (912) 478-5268. 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.

11. You will not receive compensation for your participation in this project. You will be responsible for no additional costs for your participation in this project.

12. 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, Dr. Murray.

13. You understand that you may terminate participation in this study at any time without prejudice to future care or any possible reimbursement of expenses, compensation, employment status, or course grade except provided herein, 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.

14. You understand there is no deception involved in this project.

15. 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 or at the phone numbers given (912) 478 – 5268.

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

Title of Project: Identification of Persistent Impairments in Postural Control Following Concussion

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______________________________ ________________

Participant Signature Date

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

______________________________ ________________

Investigator Signature Date

MEDICAL HISTORY QUESTIONNAIRE

GEORGIA SOUTHERN UNIVERSITY BIOMECHANICS LAB

MEDICAL HISTORY QUESTIONNAIRE

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

Subject ID ____________________ Date ____________________

Gender: Male ☐ Female ☐ Year in School: FR ☐ SO ☐ JR ☐ SR ☐ DOB: ______

Please answer the following questions about your medical and injury history:

Concussion History:

1. Have you ever suffered a concussion? YES ☐ NO ☐

   If yes, how many? ____

   Please provide a short description of the incident(s):

   ____

   ____

2. Have you ever been "knocked out" playing sports? YES ☐ NO ☐

   If yes, please provide a short description of the incident(s): -

   ____

   ____

3. Have you ever "seen stars", been confused, or been disoriented playing sports? YES ☐ NO ☐

   If yes, how many times? ____________

   In the past year? ________________

4. Have you ever lost your memory after taking a hit playing sports? YES ☐ NO ☐

   If yes, please explain:

   ____

Musculoskeletal History: (please note all injuries with significant time missed from practice/competition)

5. Have you ever sprained your ankle? YES ☐ NO ☐

   If yes, how many? LEFT: ______ RIGHT: ______ In the past year? ______

   Time missed? ____________________

   Which is your "dominant" ankle? LEFT ☐ RIGHT ☐

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

   If yes, please explain: ______________________________

   Does this injury still bother you? YES ☐ NO ☐

7. Have you ever hurt your knee? YES ☐ NO ☐

   If yes, did you ever tear a ligament/meniscus (please specify which)?: YES ☐ NO ☐

   If yes, did you have surgery? (date): ______________________________

8. Have you ever hurt your hip? YES ☐ NO ☐

   If yes, please explain: ______________________________

9. Have you ever strained/tore lower extremity muscles? YES ☐ NO ☐

   If yes, please explain: ______________________________

10. Have you ever injured your low back or had a nerve pathology? YES ☐ NO ☐

    If yes, please explain: ______________________________

11. Do you have any known balance, metabolic, or neurological disorders? YES ☐ NO ☐

    If yes, please explain: ______________________________

12. Have you had any other muscle, bone, or joint injury to your body? YES ☐ NO ☐

    If yes, please explain:

    ____

    ____

Additional Notes:

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