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Evaluation of Linear and Nonlinear Postural Stability Measurements Following Concussion

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EVALUATION OF LINEAR AND NONLINEAR POSTURAL STABILITY MEASUREMENTS FOLLOWING CONCUSSION

by

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(Under the direction of Li Li)

ABSTRACT

Sport related concussions affect nearly 1.6 to 3.8 million athletes annually in the United States. A large number of these athletes suffer from postural instability following concussion. Postural control assessment has become a recommended tool to determine readiness to return to play. Measurement of postural control through the use of center of pressure (CoP) variables may provide a sensitive evaluation following concussion and throughout recovery. **Purpose:** To evaluate a unipedal and bipedal quiet stance protocol consisting of linear and nonlinear CoP measurements with varying durations in a concussed population throughout recovery. **Methods:** Thirteen NCAA Division I Collegiate Football players (age: 20.1 ± 1.6 years, height: 178.3 ± 4.8 cm, mass: 94 ± 10.4 kg) were tested. Participants completed a quiet stance protocol for the first 8 days following injury and at return to play (RTP) under unipedal right and left leg conditions, 3 trials each for 20 s and a bipedal condition (feet together, first 20 s and full 120 s). Three trials of the unipedal stance were conducted and the mean was statistically evaluated. Linear CoP measurements evaluated were Ninety-five percent area (95area) and average velocity (Vavg); nonlinear measurements were approximate (ApEn) and sample (SampEn) entropy. ApEn and SampEn were evaluated in the anterio-posterior (AP) and medio-lateral (ML) directions. These were analyzed using a two way (base of support (BOS) x day) MANOVA as well as a Tukey post hoc analysis. **Results:** There was a significant main effect for BOS condition, however no main effect for day. No difference was observed between right and left unipedal stances. The 120 s trial and 20 s trial for the bipedal stance was significantly different for 95area, ApEn AP, SampEn AP, and SampEn ML. **Discussion:** It may be necessary to collect data for up to 120 s to reliably quantify the effects of concussion on the postural control system. In this population, both ApEn and SampEn appear to be dependent on the recording length as well as discriminate different BOS conditions**.**

INDEX WORDS: Postural stability, Quiet stance, Concussion, Mild traumatic brain injury

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1. INTRODUCTION

Sport related concussions have become a growing health concern affecting 1.6 to 3.8 million athletes in the United States annually.[1] This rate may be underestimated considering close to half or more of the number of concussions go unreported.[2] A large majority (77%) of athletes that suffer from a concussion have difficulty with balance and dizziness, and postural stability assessments have become a recommended tool to determine readiness to return to play.[3,4] Recovery from concussion is inherently individualized, and an early return to activity may increase the risk for both recurrent concussion as well as musculoskeletal injury.[5,6] According to the 4th International Consensus Statement, the majority (80-85%) of individuals that suffer a concussion recover within a week, with the most commonly utilized clinical assessment of balance, the Balance Error Scoring System, returning to normal in 3-5 days.[3,4] However, sophisticated, instrumented techniques of postural stability detect lingering deficits greater than one-week post injury.[7-20] Issues associated with the Balance Error Scoring System test include reduced sensitivity over time, poor reliability, influence of fatigue and environment, and the significant practice effect associated with repeat administrations.[21-27] Postural assessments may provide a way to identify concussion related neurophysiological changes, and more sophisticated measurements of postural stability may offer more diverse information about the postural control system.

Return to participation (RTP) prior to full recovery could have a multitude of detrimental consequences. Acutely, Second Impact Syndrome may occur in individuals who RTP before post-concussion symptoms have resolved and receive a second impact to the head resulting in cerebral swelling, brain herniation, and potentially death; however some debate the existence of this syndrome.[28-30] The dose response associated with multiple concussions can put an athlete at a 3 - 6 times greater risk of suffering a subsequent concussion.[5,31] This could potentially be due to premature RTP, as 90% of same season concussions happen within 10 days.[5] Recurrent concussions have also been associated with slowed neurological recovery, as well as an increased risk of suffering from loss of consciousness, anterograde amnesia, and confusion after a subsequent concussion.[5,32] Not only are subsequent concussions a viable risk, but the risk of musculoskeletal injuries (e.g. ACL injuries, head/neck fractures, and ankle sprains) increases nearly 50%.[6] Late life deficits are a potential concern after suffering 3 or more concussions, and include an increased risk of developing memory problems and/or Alzheimer's disease, clinically diagnosed depression, as well as fivefold increase in developing mild cognitive impairment.[33,34] Therefore, appropriate concussion management and sensitive identification of recovery is necessary to reduce the risk of further injury.

Postural stability assessments, as a recommended tool to determine readiness to RTP, can be measured through the use of center of pressure (CoP). CoP is the point of application of the sum of forces applied to the surface of support, and is dependent on the location, orientation, and mass distribution of the body in respect to the support surface.[35] In order to understand stability and essentially the postural control system, CoP position and velocity is assessed. In concussed populations linear measures, such as area and velocity, have indicated lingering postural stability deficits up to 30 days following injury, even after RTP.[7,16,36] Interestingly, previous literature suggests that CoP displacement area linearly increases for up to 2 min during quiet standing acutely following concussion.[15] However, common measurements of postural stability such as the Balance Error Scoring System and the Sensory Organization Test only evaluate postural stability for 20 s.[37] A quiet stance protocol with longer data collection may be necessary to determine recovery and properly quantify a concussion's effects on the postural control system.

Beyond linear measures, non-linear measures have recently been suggested as useful to evaluate deficits in postural stability following concussion. Entropy is used to quantify the amount of randomness and irregularity within a specific time series.[38-40] When healthy, oscillations in postural steadiness could be attributed to natural rhythms of the postural control system.[39] Therefore, changes in sway or instability may not necessarily be indicative of an abnormality in the postural control system. Motor variability may be necessarily important for an individual's ability to adapt.[41,42] A reduction in variability of the motor system could be indicative of an inability to learn or potentially an indicator of disease.[43] In diseased populations, such as Parkinson's disease, individuals show lower approximate entropy (ApEn) values and more patterned voluntary motor movements.[44] Generally, concussed individuals display reduced variability whereas healthy individuals have greater variability.[38,40,45] ApEn has shown promise at detecting differences between concussed and non-concussed individuals even when standard CoP measurements have not.[38,40] ApEn in concussed individuals, has been characterized as more regular (less variability) after injury despite having normal postural stability measured via the Sensory Organization Test.[38,40] However, Cavanaugh and colleagues used the Sensory Organization test to measure postural stability for 20 s in the acute (48 – 96 hours) period following concussion, and the literature has not evaluated ApEn later in recovery. Although multiple studies have focused on ApEn, it is heavily dependent on recording length and lacks relative consistency.[46] An alternative to ApEn that is similar but does not count self matches and is less sensitive to recording length is Sample Entropy (SampEn).[46] Therefore, when comparing biological systems SampEn may be a more appropriate measurement.[46] These nonlinear dynamic measures may be able to detect lingering deficits in individuals with a concussion and may provide a more sensitive assessment to determine recovery.

Using sophisticated outcome variables to observe postural stability following a concussion could improve sensitivity for determining RTP, thus potentially reducing the risk of further injury. Quiet stance is commonly used in the concussion literature to measure postural stability; however it is usually performed in a bipedal stance.[7,12,16,38,40] Unipedal and bipedal stances present different challenges regarding the base of support, and therefore may provide valuable information unique to the somatosensory system. Thus far in the literature, the majority of postural stability assessments last for 20 s, and some supporting evidence indicates the need for a longer testing protocol. ApEn should theoretically be dependent and SampEn independent of record length. SampleEn is a novel approach to concussion evaluation and has yet to be established in the literature as a useful tool. Therefore, the purpose of this study was to evaluate base of support and measurement duration during a quiet stance protocol consisting of linear and nonlinear CoP measurements in a concussed population throughout recovery. It was hypothesized that acutely following concussion, linear variables (95area and Vavg) would be elevated and nonlinear variables (ApEn and SampEn) would demonstrate reduced variability. Over the testing period these measures would indicate recovery. Secondarily, that a bipedal stance would display reduced linear (95area and Vavg) values and higher variability in nonlinear (ApEn and SampEn) measurements compared to a unipedal stance due to a greater base of support. Lastly, the linear variables and ApEn would be time dependent, but SampEn would be time independent during the bipedal stance.

2. METHODS

Participants

Thirteen NCAA Division I football players from a large Southeastern university were tested following a concussion identified by a certified athletic trainer and physician (Appendix C; *Table 1*). Eight of the 13 participants had a history of prior concussion (0.9 ± 1.0). All participants denied current and past history of postural stability, neurological, metabolic, or vestibular disorders. All participants provided written informed consent prior to participating as approved by the local Institutional Review Board. The exclusion criterion included anyone who had an injury (previous concussion, or lower extremity injury) in the last 6 months, or was not fully participating. In order to maintain a homogenous sample to control for coaching or athletic training influences our specific inclusion criteria included only members of the University's varsity football team.

Instrumentation

Center of Pressure (CoP) data was collected from a single force platform (model OR-6, AMTI, Watertown, MA, USA) at 1000 Hz, processed using Vicon Nexus 1.8.5 (Vicon Motion Systems, Oxford, UK), and down sampled to 10 Hz to be analyzed in Microsoft Excel 2010 (Microsoft, Redmond, WA, USA). The force plate was zeroed out prior to each testing session.

Procedures

All participants were recruited through their respective certified athletic trainer. Once they agreed to participate they signed an informed consent and completed a health history questionnaire (Appendix C; *Figure 1*). The participants completed the quiet stance protocol for the first 8 days following injury plus on the day they RTP. The RTP protocol was set in place by the medical staff of the University's Athletic Training department and was consistent with the 4th International Consensus Statement (Appendix C; *Figure 2*). Individuals were excluded if they missed more than one day of testing. If a participant did miss one day, his data for the following day was copied and put in place of the missing day.

The quiet stance protocol began with the unipedal task of standing barefoot with the foot in the center of a single force plate while the non weight-bearing knee was flexed at approximately 90^{O}. The participant held this stance for at least 20 s, however only the first 20 s was analyzed. Three trials on the right foot and 3 trials on the left foot were completed. If a participant was unable to maintain the stance for the full 20 s, they attempted the trial again. After the unipedal stance, the participant was instructed to stand on the force platform as still as possible for 120 s with both feet together (Appendix C; *Figure 3*). All trials were initiated and terminated with a verbal cue from the investigator.

Data Analysis

The independent variables included BOS (4) and days (9). The first eight days immediately following injury were evaluated as well as RTP. Four BOS conditions were analyzed 1) unipedal right 2) unipedal left 3) bipedal for 120 s 4) bipedal for the first 20 s of the 120 s trial. RTP is the day that the participant returned to full activity without any restrictions. On average participants returned in 13.0 ± 5.4 days. Dependent variables consisted of linear measurements: 1) 95area and 2) Vavg and nonlinear measurements: 3) ApEn in the anterior-posterior direction (AP), ApEn in the medial-lateral (ML) direction and 4) SampEn in AP and ML. The mean of the 3 trials for each unipedal test was analyzed.

Statistical Analysis

Descriptive characteristics of all participants were collected including age, height, body mass, sport, and previous history of concussion (Appendix C; *Figure 1*). One multivariate analysis of variance (MANOVA) was performed, which included all variables of interest (95area, Vavg, ApEn AP and ML, SampEn Ap and ML). If significance was observed, the data was further explored with simple contrasts (for potential interaction and day) and Tukey post hoc testing (for stance). Alpha was set at 0.05. The data was checked to see if it violated the following assumptions: 1) normality to ensure the scores for each condition are normally distributed around the mean, 2) homogeneity of variance to ensure each population has the same error variance, and 3) sphericity of the covariance matrix to ensure the F ratios match the F distribution. Where necessary, adjustments to alpha levels were made if assumptions were violated.

3. RESULTS

We did not observe a statistically significant difference across days ($F(48, 2105) = 1.041$, $p=0.397$, partial $\eta^2 = 0.019$.) However, there was a main effect for BOS ($F(18, 1208) = 64.708$, $p<0.001$, partial $\eta^2 = 0.471$). Therefore, individual days were collapsed into an average and compared amongst BOS conditions. Univariate follow-up tests displayed differences by BOS for each dependent variable (95area $p<0.001$, Vavg $p<0.001$, ApEn AP $p<0.001$, ApEn ML $p<0.001$, SampEn AP $p<0.001$, SampEn ML $p<0.001$). No differences between right and left unipedal stances were found. Significant differences amongst each BOS condition differed for each dependent variable (Appendix C; *Table 2*).

Ninety-five percent Area

Right, left, and bipedal for 120 s were all significantly greater than the bipedal stance for 20 s (Appendix C; *Figure 4*).

Average Velocity

Vavg for right unipedal stance was significantly greater than the bipedal stance for 120 s and 20 s. Left unipedal stance Vavg was significantly greater than the bipedal stance for 120 s and 20 s. There was no significant difference for Vavg between the different durations of a bipedal stance (Appendix C; *Figure 5*).

Approximate Entropy

ApEn AP, for both right and left unipedal stance, was significantly greater than the bipedal stance for 120 and 20 s. Left unipedal stance ApEn AP was also significantly greater than the bipedal stance for 120 s and 20 s. The bipedal stance ApEn AP for 120 s was significantly lower than the value for 20 s (Appendix C; *Figure 6*). ML had similar results as in the AP; however, the bipedal stance for 120 s was not significantly different than 20 s (Appendix C; *Figure 7*).

Sample Entropy

In AP (Appendix C; *Figure 8*) and ML (Appendix C; *Figure 9*) the unipedal stance SampEn had significantly higher values than the bipedal stances. The bipedal stance for 120 s was significantly reduced compared to 20 s.

4. DISCUSSION

The purpose of this study was to evaluate base of support and measurement duration during a quiet stance protocol consisting of linear (95area and Vavg) and nonlinear (ApEn and SampEn) CoP measurements in a concussed population throughout recovery. The principal finding of this study was the significant difference amongst the four different BOS (right unipedal, left unipedal, 120 s bipedal, 20 s bipedal) conditions. This indicates that diverse postural stability assessment protocols may result in different sensitivities of CoP measurements. Impaired postural stability is a cardinal feature associated with sports related concussions and the usefulness of certain CoP measurements at displaying deficits have been observed in the literature. However, few studies have evaluated linear and nonlinear CoP measurements amongst different BOS conditions for continuous days post-concussion and at RTP. Although most concussion related postural stability assessments generally measure for 20 s,[38,40,47-49] our results suggest it may be necessary to perform these assessments for up to 120 s. The current observations also support the use of a uni- and bipedal testing protocol following a concussion, which is consistent with current testing methods such as the Sensory Organization Test, and Balance Error Scoring System.[37] Lastly, both ApEn and SampEn measures were dependent on measurement duration.

The current study suggests values of 95area reported here are similar to those previously reported in concussed individuals.[15,18] CoP displacement is considered a first order variable and a measurement of body sway.[50] Displacement measurements return to normal values before higher order variables such as velocity.[12] Powers and colleagues observed an elevated CoP RMS displacement and RMS velocity acutely following concussion, but at RTP RMS displacement returned to healthy values, while RMS velocity remained elevated.[12] Slobounov and colleagues evaluated the CoP area percent increase from standing with eyes open to eyes closed. This value remained elevated 15 days following injury when compared to an athlete's baseline value. However, the magnitude of this increase was not correlated with the injured athletes' rate of recovery over the course of a year, likely due to the fact that no significant differences existed 30 days following injury.[51] Therefore, the authors suggest that CoP area may not be sensitive enough to detect residual postural control deficits beyond 15 days. Our results imply that in order to reliably quantify deficits using displacement, the collection period should last closer to 120 s. This is consistent with recent reports indicating an increase in area of CoP for up to 120 s acutely following concussion.[15] However, the methodologies used in the aforementioned studies vary from our experimental protocol and should be taken into consideration. Deficits in CoP displacement or area may dissipate more quickly than higher order variables such as velocity, or it is possible that postural stability assessments are not allowing an individual enough time (only 20-60 s) to display those deficits.

Velocity is a higher order derivative of displacement and may represent different information, such as direction and intensity of movement.[50] Results here suggest that Vavg is not influenced by duration of testing and may be a more consistent CoP source compared to 95% area. Comparatively, our values for Vavg are consistent with values of diseased populations, such as Parkinson's.[52] During standing, somatosensory information is a crucial component of sensory information received and a large average velocity could indicate poor somatosensory feedback or potentially inaccurate information about the body position.[52-54] Previous literature suggests that disrupted somatosensory feedback can cause the CoP to drift and produce a large area of displacement and large velocity.[55] Since the postural control system relies on velocity information to produce anticipatory muscle activation, an elevated velocity may indicate impaired postural stability.[50] Velocity serves as a postural stability measurement and provides an indirect way of evaluating neurophysiological abnormalities. [47] In an attempt to understand the effects of concussion on the central nervous system and if it has returned to a healthy capacity, Vavg appears to be the strongest measure tested in this study.

In situations where standard CoP measures are not able to detect deficits within the postural control system following a concussion, nonlinear dynamics may be useful. Cavanaugh and colleagues observed a reduced variability immediately following concussion in athletes with steady and unsteady postural stability as measured on the Sensory Organization Test.[40] We have observed a value very similar to the concussed population in the Cavanaugh study. Speculation about the nature of this decrease in variability centers around two ideas 1) a postural mechanism and co-contraction of the lower limb (tibialis anterior and gastrocnemius) and therefore less sway and a more regular pattern of CoP oscillations 2) axonal injury during concussion that may cause distorted interaction amongst neurons in the brain, making the regions of the brain less coupled and increasing regularity.[39] In either case, the literature suggests entropy was able to detect changes in the postural control system following concussion where typical measures of stability were not.[38] Also, chronic deficits have become apparent through the use of entropy.[11] Formerly concussed individuals displayed a lower CoP oscillation randomness up to 9 months following injury.[11] Although these values may provide valuable information, our results suggest that ApEn in the AP direction is sensitive to record length, which is consistent with the literature.[46] Therefore, in anticipation of this potential bias of ApEn, SampEn was also measured. According to Richman and Mooreman, SampEn should be independent of record length and an overall more consistent measure than ApEn.[46] However, our results do not covey this concept. For both the AP and ML direction SampEn displayed significant differences amongst the record lengths of

120 s and 20 s. One potential reason for this could be the methodology and the sampling frequency used, which in our case was 1000 Hz at collection and down sampled to 10 Hz before processing. Both ApEn and SampEn are extremely sensitive to parameter choices, and although Yentes and colleagues state that SampEn is more reliable, they observed this in short data sets only (N≤200). It also must be considered that this is a novel measure in evaluating a concussed population, and due to the nature of the injury we may not detect the general trend seen in healthy individuals. Although, in theory, SampEn may be a more reliable measure compared to ApEn, our results suggest that they are both dependent on the time series and both variables are sensitive to different BOS conditions.

These results may influence the way clinical data is collected and used in the management of concussion. Common clinical assessments of postural stability as discussed earlier measure quiet standing for 20 s, and research suggest that deficits return to normal within 3-5 days.[3] However, our results, in agreement with Gao, indicate that a longer testing protocol (120s) may be necessary to reliably quantify the postural deficits following concussion. Recovery from concussion is inherently individualized, and an early RTP may increase the risk for both recurrent concussion as well as musculoskeletal injury.[5,6] Interestingly, our results denote no main effect for testing day, which could mean one of two things 1) athletes were not actually recovered at RTPor 2) none of these outcome measurements, both linear and nonlinear, were sensitive to recovery. From the recent surge of research suggesting postural deficits last longer than the average 7 - 10 day timeline of recovery stated in the 4th CIS, it is possible that the postural stability of our population may not have recovered. The use of virtual reality environments, gait analysis, and quiet and dynamic stance testing protocols suggest deficits remain 10 days from injury, at RTP, 30 days following injury, and even up to 1 year.[8,9,12-20] It is critical that clinicians have reliable, valid, and quantitative measurements to evaluate when an athlete has returned to healthy functioning. These results provide information about different testing methods under various conditions to give a broad range of information for evaluation.

In this research study we carefully controlled for any major limitations, however some factors were apparent and should be discussed. First, data were collected for consecutive days following concussion (1 - 8) and at RTP, however not all participants completed every day of testing due to conditions out of our control such as travel. However, our strict inclusion criteria required that anyone participating could not miss more than 1 day of testing in the first 8 days. This also limited our sample size. With a strict inclusion criteria and the attempt to maintain a homogenous sample of football players to control for coaching or athletic training influences we were limited in participants. One of our exclusion criteria required that anyone participating did not have a concussion or previous lower extremity injury within the last 6 months. Although we did have the help and support of the athletic training staff, it is possible that an injury went unreported, however all athletes were able to perform each task and we do not believe this could compromise the validity of our results.

In conclusion, it appears that diverse protocols may result in different sensitivities of CoP measurements in concussed individuals throughout their recovery process. None of the dependent variables displayed a significant difference between the right and left unipedal stance, which indicates it may only be necessary to test either left or right if evaluating a unipedal stance. Conducting a full 120 s quiet standing trial may be critical to identify potential deficits, especially when using a displacement variable. SampEn does not appear to be independent of time based on our results, and the use of either ApEn or SampEn will provide similar information. Finally, future research should assess the ability of SampEn to quantify deficits following concussion and evaluate its necessity in a concussed population.

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APPENDICES

Appendix A: Delimitations, Assumptions, Hypotheses

Delimitations

- Georgia Southern University Varsity football athletes only
- Current Georgia Southern Athletic Department concussion assessment and RTP protocol dictates when and how long we are able to test a participant

Assumptions

- Our analyses using CoP Vavg, 95area, ApEn and SampEn are valid and reliable measurement of postural control
- Quiet stance is a consistent measure and there was not a difference in performance in healthy individuals
- Participants gave full effort

Hypotheses

- HO1: There would be no differences across days for linear and nonlinear variables.
- HA1: There would be an elevation in linear variables and reduced variability in nonlinear variables acutely following concussion, which would recover by RTP day.
- HO2: There would be no differences across BOS conditions in linear and nonlinear variables.
- HA2: Bipedal stance would display reduced linear values, and higher variability in nonlinear measurements compared to unipedal stance.
- HO3: There would be no differences amongst a 120 s and 20 s trial of bipedal quiet stance in linear or nonlinear variables.
- HA3: Linear variables and approximate entropy would be time dependent, but sample entropy would be time independent during the bipedal quiet stance.

Appendix B—Literature Review

Concussions, also known as mild traumatic brain injuries (mTBI), affect nearly 1.6 to 3.8 million athletes annually.[1] The majority of these sport related concussions happen in contact sports such as football and soccer.[2-5] Although the reported incidence of this injury has increased over the past decade, this type of neurologic injury was studied nearly 3,000 years ago.[6] In the year 900, Rhazes identified a concussion as "abnormal transient physiologic state without gross brain lesion," and he termed this injury Commotio Cerebri.[6] Not only was it defined many years ago, but during the Era of clinical understanding the "learned Doctor Read" depicted this injury with a nearly textbook description of how we identify a concussion today.[6] Things such as singing in the ears, falling after the blow, swooning for a time, slumbering, dazzling of the eyes and a giddiness which passes rapidly were some examples, these signs are still apparent this day in age.[6] Today, common symptoms include headache, dizziness, concentration difficulties and confusion.[2,3,5,7,8] These symptoms can be attributed to a complex cascade of neurometabolic events that take place in the brain following a concussion.[9]

Once the impact occurs, depolarization and initiation of action potentials is followed by voltage-depend K^+ channels opening, which lead to an increased extracellular K^+ concentration. This massive efflux of potassium in the cell causes the membrane ion pumps have to increase activity in order to maintain homeostasis. More energy is needed for this; therefore hyperglycolysis ensues to produce more ATP (adenosine triphosphate). Lactate begins to accumulate and simultaneously calcium begins to enter the cell and sequesters in the mitochondria essentially impairing oxidative metabolism. The production of energy (ATP) begins to plummet, and apoptosis of the cell will occur. This cascade of events causes an energy crisis, and unfortunately the brain is unable to store ATP like skeletal muscle, therefore ATP must come from plasma glucose or mitochondrial oxidative production. Due to the decrease in cerebral blood flow, and hyperglycolysis that is taking place, there is a large gap to fill.[9] However, there is no structural damage to the brain that could potentially be observed by standard neuroimaging techniques such as magnetic resonance imaging or computed tomography[10,11] Since this injury cannot be seen it is hard to detect, leaving health care professionals reliant upon of the honesty of athletes. Returning an athlete prior to full recovery could potentially put them at risk for further injury and complications later in life.[5] Recurrent concussions are also associated with impaired neurological function, mild cognitive impairment, depression, early onset of Alzheimer's disease, and potentially Chronic Traumatic Encephalopathy (CTE).[12-17]

An important factor in concussion assessment and management are the coaches and health care staff; their awareness to this injury is critical. Self-report rates are extremely low, over half of high school football players who suffered a concussion didn't report it because they didn't think it was serious enough to warrant medical attention.[18,19] With reporting rates this low, it is important to understand the awareness and knowledge that coaches, players, and parents have about concussions in order to properly educate and to hopefully increase the rate of reporting. Although our understanding of mild traumatic brain injuries have improved since the 80s and 90s, there is still a significant number of people that hold inaccurate beliefs about head injuries.[20] Players, arguably the most important component when it comes to properly diagnosing and treating a concussion, are not reporting most concussive events to the supervising adult.[19] Most concussions sustained by high school athletes were not reported, although both concussion knowledge and attitude assisted in their reporting behaviors.[19] Increased concussion knowledge and attitude increased reporting prevalence as well as decreased prevalence of players participating while still symptomatic.[19] Almost half of all high school athletes fail to comply with AAN RTP guidelines.[21] Compliance rates were higher when using the Prague RTP guidelines, however one in six athletes returned prematurely.[21] The potential implications of returning to play prematurely or not reporting a concussion could be catastrophic and result in further injury or long term neurological deficits.[5,12] Therefore these findings emphasize the need for educating players especially at a young age.

Educating athletes is one hurdle, but it is also important for coaches to be well versed in detecting and assessing a concussion, especially if there is limited or no access to a certified athletic trainer (ATC), mainly at the High School level. According to the National Athletic Training Association, only 42% of high schools have access to an ATC. Formal coaching education is predictive of proper identification of symptoms, signs and common misconceptions of a concussion.[22,23] However, several misconceptions do still exist among coaches, therefore presence of health care professionals and continued education should be implemented. When assessing knowledge of coaches their greatest strength was recognizing a concussion, but greatest weakness was the management of a concussion.[24] Identification of a concussion does not seem to be the issue, however return to play decisions and how to manage the recovery process may be the greatest downfall for the coaches. Coaches who had a history of concussion, or attended a workshop on concussions scored higher on the recognition and management section of their evaluation, respectively.[24] Similarly, coaches are more knowledgeable about concussions than the general public.[25] Also, coaching conferences and associations provided the most common source of concussion information.[25] This same study also indicated coaches were compliant with return to play protocols, unlike the athletes found in the research done by Yard and Comstock in 2009. Coaches play a large role in the safety of student-athletes, and it is important for them to understand the nature of concussive injuries.

It appears that educational resources such as clinics, conferences, associations, or a background in coaching education leads to more knowledge, and safer attitudes about concussions. However, when sampling Physicians and providing a group with the CDC's "Heads Up" Toolkit there was no difference between the intervention and control group.[26] However, this could be due to the extensive education that medical doctors receive compared to coaches. Insufficient research is provided on the implications of this knowledge and conservative attitude of coaches in a game type situation. Further research is necessary to understand how and if the knowledge is implemented when it matters most.

Awareness is a crucial component of concussion management, but once the injury is suspected a thorough assessment is necessary. There are various assessment tools used in concussion management with differing levels of reliability, validity, sensitivity, and specificity. A common tool used in the assessment of a concussion is balance testing. The most feasible and cost effective source of balance testing is the Balance Error Scoring System (BESS). Normal change in BESS post injury is an increase in 6 or 7 errors from baseline, and these deficits usually recover within three to five days.[12,27] Intrarater reliability on the total BESS score ranges from 0.60 to 0.98, with moderate reliability as <0.75 and good reliability >0.75.[27-29] However, interrater reliability is lower ranging from 0.57 to 0.96 on total BESS score, and individual stance reliability ranging from 0.44 to 0.83.[29] Interrater and intrarater minimum detectable change (MDC) for total BESS score is 9.4 and 7.3 points, respectively.[29] This indicates that for a different rater there would have to be a 9.4-point change in score to detect any differences accounted for by balance and not the rater. Intrarater MDC was lower, indicating it may be more reliable to use the same rater when scoring BESS. Using the same rater, and to evaluate BESS three times to average the scores together for a final score may be the most reliable way to administer this test.[27] At the time of injury sensitivity of the BESS is very poor (0.34), however specificity is good (0.91).[30] Specificity ranges from 0.91 to 0.96 from time of injury to day seven.[30] Not only does the BESS have reliability issues, but it also lacks sensitivity. BESS also has improvements (reduced errors) in repeat test performance.[27] Over the course of an athletic season there are clinically significant improvements in BESS performance in women's soccer, women's volleyball, and in control subjects, indicating a potential practice effect.[31] These groups were tested 90 days apart, yet significant improvements were observed indicating a practice effect can persist over the course of an athletic season.[31] Other limitations to BESS include athletes performing poorly when fatigued or suffering from functional ankle instability.[27] The environment and circumstances may play a role in the results of the BESS test, making it difficult to rely upon. Using a revised BESS method consisting of four conditions (single leg and tandem leg on both firm and foam surfaces) provided a more reliable measure in a sample of high school football athletes.[28] This modified BESS increased reliability and reduced the practice effect when using three trials of the four conditions.[28] BESS is a commonly used clinical assessment of postural stability, but it is clear that along although it is feasible, it has many limitations.

Assessment of a concussion consists of more than just a balance assessment; neurocognitive function also plays a large role in the evaluation. Immediate neurocognitive effects of concussion may be seen even without loss of consciousness (LOC), posttraumatic amnesia (PTA), or physical neurological abnormalities, such as a change in gross neurological status.[32] Rarely are LOC (<10% of the time) and PTA (<25% of the time) observed following a concussion.[33] However, PTA and LOC are often the main factors used in concussion guidelines.[34,35] A commonly used grading system for concussion is the revised Cantu scale, incorporating both LOC and PTA. A grade 1 (mild) concussion would consist of no LOC, less than 30 minutes of PTA and less than 24 hours of symptoms. A grade 2 (moderate) involves LOC less than a minute or PTA greater than 30 minutes but less than 24 hours, or symptoms greater than 24 hours but less than 7 days. A grade 3 (severe) concussion entails LOC greater than a minute, or PTA greater than 24 hours, or symptoms greater than 7 days.[34] Cantu also suggests that grading concussion severity should not be completed until all post-concussion symptoms have resolved.[34] Cantu proposes that PTA, anterograde and retrograde, is an essential component to the concussion evaluation, and any athlete still suffering from post-concussion symptoms at rest or exertion should not return to their respective sport.[35]

Normal neurocognitive changes are observed as a 3 to 4 point increase in total score of the Standard Assessment of Concussion (SAC) and usually recover within two days.[32] SAC has a sensitivity of 0.90 and specificity of 0.91 at the time of injury, and is the most commonly utilized component of a clinical exam.[30,36] SAC is administered to an athlete following concussion. It is a series of orientation questions (What month is it? What is the date? What day of the week is it? What year is it? What time of day is it?) followed by immediate memory questions that requires the athlete to recall five words. There are also concentration (numbers backwards and months of year in reverse order) and delayed recall questions that ask the athlete about the original five words that were presented at the beginning of the test. SAC is easy to administer, feasible and has a relatively high sensitivity, hence why it is so commonly used. More advanced cognitive assessments are also used following injury, such as computerized and paper and pencil neuropsychological assessments.

The most commonly used neuropsychological test is a computerized neuropsychological test.[37] Similar to the Balance Error Scoring System, neurocognitive tests such as the ANAM

(Automated Neuropsychological Assessment Metrics) have significant practice effects in a healthy sample of college football players.[38] ANAM was also ineffective at properly identifying athletes with a concussion, as their post-concussion scores did not differ from baseline.[38] The Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) is a computerized neuropsychological test that may be able to detect neurological abnormalities in athletes who are symptom free.[39] It is also difficult to sandbag at baseline even with motivation, instruction, and experience with the test.[40] However, it lacks reliability and nearly half of healthy participants taking ImPACT were marked as impaired at different time points.[41] Neuropsychological tests should be used with caution because of the single test sensitivity, ANAM (0.28), pencil and paper assessments (0.44), HeadMinder (0.79), and ImPACT (0.79).[38,42] Neurocognitive testing should not be the sole factor in the assessment of a concussion, and seeking the advice of a neuropsychologist would be wise. Combining neurocognitive assessments with a postural control assessment and symptom inventory provides a great degree of sensitivity in identifying a concussion. Combining either pencil and paper tests, ImPACT, or the HeadMinder CRI with postural control assessment and symptom inventory sensitivity becomes nearly 90%.[42] However, using one of these tests alone provided only a 70% sensitivity in a population of Division I Student-Athletes.[42] This supports the notion that a multifaceted approach is significantly more effective in properly identifying individuals with a concussion.

Other methods of assessment include structural and functional imaging. Most sport related concussion are associated with normal imaging, however computed tomography (CT) may be able to indicate an intracranial hemorrhage or contusion if that is present.[10] Nevertheless, CT has no utility in diagnosing or assessing a concussion.[10] Also, magnetic resonance imaging will not be useful in the identification of a concussion because a concussion is defined as a functional deficit, not a structural injury, therefore MRI would not be a practical assessment tool.[10] Diffusion tensor imaging tracks water molecules through white matter and has been used to assess white matter abnormalities after concussion.[10,43] A group of concussed adolescents displayed an increase in fractional anisotropy (FA) and a decrease in mean diffusivity (MD) compared to their control counterparts.[43] However, conflicting evidences shows a reduction in FA following a concussion as well.[10] There is opposing thoughts as to whether an increase or decrease in FA is detrimental, however a change in FA may be pathological. Functional magnetic resonance imaging (fMRI) also shows promise in the assessment of concussion. fMRI is based on the relationship between blood flow and neuronal metabolism and observes the different magnetic states of oxygen-rich and oxygen-poor blood through the blood-oxygen-level-dependent (BOLD) contrast technique.[11] There have been observed differences in BOLD signal patterns in concussed compared to control subjects and in concussed subjects when compared to baseline values.[44,45] Some advance imaging techniques (DTI, fMRI) show promise in the evaluating of a concussion, however further research is necessary to justify using these as assessment tools.

Overall, in order to properly identify a concussion multiple assessment tools are necessary. Once the assessment is complete, each concussion should be treated individually. The recovery process is not consistent throughout the injured population but some similarities are observed in standard assessment tools. On average, it takes about 2-3 days for SAC values to return to baseline, 3-5 days for BESS, and 7 days for a graded symptom checklist total score.[12,32,46] These three assessment tools recover independently of one another. This also indicates that BESS and SAC likely a practice effect due to the fact that they recover before symptoms.

Evaluating recovery and trying to determine when someone is ready to return to play is a difficult task, especially with the practice effects observed in balance and cognitive assessments that may exist in the clinical measures commonly used. There are more sophisticated measures that may be useful in tracking recovery, electroencephalographic (EEG) recordings. This method has been useful in identifying abnormalities in electrical brain activity in injured populations on the day of injury and 8 days later, but not 45 days later.[46] Additionally, it identified differences between two groups of different concussion severity (mild vs. moderate), using TBI Index.[47] TBI Index is an index of brain dysfunction based on brain electrical activity. TBI Index was also associated with length of time to return to play, and although clinical measures may indicate recovery within a week, physiological recovery may extend much longer, hence greater than a week, but less than 45 days.[46,47] Virtual time to reality (VTC) measurements have also been able to detect lingering deficits up to 30 days following injury in an asymptomatic and healthy population.[48]

Predictors of recovery have become a useful tool in understanding the potential duration of a concussive injury. LOC, PTA, retrograde amnesia, GSC total score, and posttraumatic migraine have all been associated or even predicted protracted recovery.[7,49,50] LOC was the greatest predictor of protracted recovery; athletes that suffered from LOC had a 4.2 times greater risk of protracted recovery.[49] Even though LOC and amnesia are not necessary for a concussion to occur, they may predict a longer recovery period.[49] Also, athletes with posttraumatic migraine were 7.3 times more likely to have protracted recovery (greater than 20 days).[50] It may seem beneficial to have a symptom free waiting period, however research suggests that this does not influence recovery, or reduce risk of a subsequent concussion.[51] In fact, those with a symptom free waiting period had a greater number of repeat concussions than the group with no symptom free waiting period, but did return to play relatively early.[51] Risk of repeat concussion may be due to the increased vulnerability in the first 7 to 10 days because of the neurometabolic cascade following a concussion, rather than the symptom free waiting period.[7,51] Each concussion recovers different and must be give its own timeline. However, these predictors of protracted recovery could help provide insight to coaches and health care professionals about the expected length of recovery.

Those who have suffered a concussion are at a three to six times greater risk of suffering a subsequent concussion.[5,7,52] Not only is this risk of a subsequent concussion considerably high, but also previous history of concussion is associated with slower neurologic recovery.[7,48] It is possible that there may not be an actual increased risk, but instead a reflection of cumulative time spent playing a contact sport.[53] In a population of healthy athletes with three or more concussions, scores were significantly worse on the verbal memory composite of ImPACT, but no other subscore.[54] There are no significant difference between those with three or more concussions and healthy controls for visual memory, reaction time, processing speed, and post-concussion scale composite scores.[54] Although these results were inconclusive, there is modest evidence that athletes with a history of three or more concussions have lingering memory deficits. Similar results were found in jockeys with a history of multiple concussions and cognitive performance, even after a three-month window for recovery.[55] Conversely, no detrimental cumulative effects were seen in neuropsychological testing in a population of University Football players with two or more concussions.[56]

Electrophysiological testing may be a better resource to identify underlying abnormalities that remain undetected in neuropsychological testing. Event-related potentials (ERPs) have been useful in identifying subtle alternations in cognitive related waveforms.[57] Specifically when using sustained posterior contralateral negativity (SPCN) waveform component, athletes with three or more concussions exhibited significantly reduced SPCN amplitude relative to their non-concussed and concussed (one or two previous concussions) athletes.[57] SPCN is associated with the visual information in working memory.[58] SPCN significantly correlates with visual memory capacity estimate (K) and therefore SPCN can be a valuable component in the neurophysiological index of visual working memory (WM) capacity.[57] A change in the neurophysiological index of WM storage may be a more sensitive objective measure of a working memory abnormality, which could worsen with an increase in head impacts.

Self-reported symptoms tend to resolve within a week of injury.[12,49,51] However, with an increase in history of concussions, neurological recovery becomes delayed, potentially causing a longer duration of symptoms.[7] Also, symptom reporting does not differ in athletes with a history of concussion.[59] However, there is conflicting research on the topic of symptomology, as athletes with a history of three or more concussions reported more PCS symptoms in the off season than athletes with only one or two previous concussions.[60] Three or greater concussions may include a larger range of concussions, creating a more significant difference between the groups. Many research articles have used 3 or more concussions as the threshold for a significant increase in detrimental effects.[7,54,57] Even with resolution of behavioral symptoms, there are deficits lingering in those with a higher number of previous concussions. However, the literature regarding cumulative effects is inconclusive and further research is necessary to understand how to manage athletes that have a history of multiple concussions.

However, there is currently evidence to suggest that retired NFL players that have suffered mild traumatic brain injuries struggle with cognitive impairments.[13,14,61,62] The spouse reported prevalence of cognitive impairments in retired NFL players is as high as 35% in a relatively young population (64.2 years).[61] Studies done with Mild Cognitive Impairment (MCI) are usually performed in older populations, but have a much lower prevalence rate, usually fewer than 5% for men under the age of 75.[61] Retired NFL football players who have suffered three or more concussions are at a three times greater risk of being diagnosed with depression, and struggling with significant memory problems, while also there is a fivefold increased prevalence of Mild Cognitive Impairment (MCI) diagnosis.[13,14] Although depression, cognitive impairments and memory problems are not predictive of CTE, they are clinical representations of CTE and lead us to believe that repetitive brain injuries may lead to chronic traumatic encephalopathy.

Repetitive mild traumatic brain injuries may impact neurologic function, but it may also contribute to a progressive tauopathy known as chronic traumatic encephalopathy (CTE).[16,17,63] CTE correlates with increased duration of football play, survival after football, and age at death.[17] The pathology behind CTE consists of tau protein bundles, atrophy of the cerebral hemispheres, medial temporal lobe, thalamus, mammillary bodies, and brainstem, as well as a ventricular dilation and fenestrated cavum septum pellucidum.[16] CTE presents clinically as memory disturbances, behavioral and personality changes, Parkinsonism, as well as speech and gait abnormalities.[15,16] Research looking at 85 post-mortem brains with histories of mild traumatic brain injuries, found that 68 subjects showed evidence of CTE.[17] The majority of these experimental subjects were football players (n= 50), with some hockey players, boxers, and wrestlers, as well as military veterans. CTE or CTE-motor neuron disease (CTE-MND) was diagnosed in 51 cases of the mild traumatic brain injury group, which was 60% of the mild traumatic brain injury sample, and 75% of all CTE cases.[17] Among these 51 cases of CTE or CTE-MND, seven deaths resulted from suicide, six others expressed suicidal tendencies at some point during their life, and six deaths from drug or alcohol overdoes.[17] CTE-MND is a degeneration of lateral and ventral corticospinal tracts of the spinal cord, marked loss of anterior horn cells from cervical, thoracic and lumbar spinal cord with gliosis, and TDP-43 or pTDP-43 positive inclusions in anterior horn cells and white matter tracts of the spinal cord.[63] Contact sports, including boxing, football, and hockey, may be associated with TDP-43 proteinopathy, that could potentially become motor neuron disease.[63]

Currently, CTE can only be diagnosed neuropathologically and post-mortem, much like other neurodegenerative diseases.[15] However, researchers are now using debated and different diagnostic techniques such as biomarkers (measuring beta amyloid and tau in the CSF and blood), structural neuroimaging, biochemical neuroimaging, and genetic susceptibility markers to help diagnostic accuracy in Alzheimer's Disease (AD).[15] Similar diagnostic techniques may be useful in diagnosing CTE pre mortem. CTE involves neuropathological changes that could potentially be seen with Volumetric Magnetic Resonance Imaging (MRI) due to the whole brain atrophy that may occur in CTE.[15,16] DTI may also be a useful tool because it is sensitive to axonal injury, which is a hallmark of traumatic brain injury.[15] Other tools such as Functional Magnetic Resonance Imaging (fMRI), Magnetic Resonance Spectroscopy (MRS), Positron emission tomography (PET), and single photon emission computer tomography (SPECT) are all being discussed as potential instruments to help identify CTE.[15]

Thus far, this review has discussed multiple subtopics of concussion including awareness, assessment, recovery, cumulative effects, and chronic traumatic encephalopathy. The subsequent section of this review will thoroughly discuss the impact concussions may have on postural stability, postural control, and different methods to help identify stability deficits following mTBI. An objective measure of postural stability has the potential to provide clinicians with an understanding of when someone is ready to return to play.

Postural control is a result of an individual's interaction with a specific task and environment to maintain stability and orientation.[64] Postural stability has been defined as the ability to maintain position of the body and center of mass (COM) within specific boundaries of space, and COM is defined as a point that is at the center of the total body mass.[64,65] Postural stability can be considered a measure of balance, and understanding postural stability must begin with understanding the central nervous system (CNS). Balance is controlled by feedback and feedforward systems in the central nervous system (CNS), which includes integrating sensory information from three systems: visual, somatosensory (proprioceptive), and vestibular systems.[66-69] The role of the CNS in maintaining upright posture can be divided into multiple components, sensory organization, cognitive processing and muscle coordination.[66,67] Sensory organization involves timing of movement, direction, and amplitude of postural actions based on the information obtained from the sensory systems.[66] Muscle coordination is related to the temporal sequencing and distribution of muscle contractions in the lower extremities and trunk of the body to maintain balance.[66] The cognitive portion is less understood but plays a role in the maintenance of stance. Overall, control of stability is maintained by the CNS through the integration of multiple complex systems.

Three main sensory systems control upright stance, but the primary system relied upon is the visual system. The visual system has three components, the central, ambient and retinal slip.[70] The central visual system specializes in object motion perception and recognition, whereas the other two systems are sensitive to movement and tend to dominate both perception of self-motion and postural control.[70] The somatosensory system relies heavily on the proprioceptive and cutaneous input from the muscle spindles (proprioceptive), mechanoreceptors (nervous system information), and golgi tendon organs (GTO).[70] Lastly, the vestibular system keeps the eyes fixed on a stationary target in the presence of head and body movements as well as maintaining balance in combination with information from the visual and somatosensory systems.[67] The vestibular system consists of semicircular canals of the vestibular labyrinth to sense angular acceleration and converts it into velocity information sending it through the vestibuloocular reflex pathways to the ocular muscles.[67] These three systems work together to maintain upright quiet stance. Young adults predominantly use the visual system to maintain optimal posture.[70] However, research still seeks to understand which system is affected the most following concussion. This has been studied by removing a sensory system (eyes closed, foam surface or vestibular interruption) to understand the role of each system individually following a concussion.

Balance assessments that interrupt different sensory inputs help understand the role of each system and involve tests such as the Sensory Organization test (SOT) and the Clinical Test of Sensory Interaction and Balance (CTSIB), both of which require a sophisticated force plate system. These assessments challenge the central nervous system by eliminating one or more sources of sensory input, visual with eyes close, somatosensory with a foam surface, or vestibular with visual-conflict dome.[66,69,71] This technique combines three visual and two support surface conditions during the assessment of postural stability. Eyes may be open, closed, or under visual conflict in a visual-conflict dome.[69,71] This visual-conflict dome moves with the subject’s head movements but does not allow peripheral vision. The two support surfaces are a firm surface and compliant foam surface. Another balance assessment that does not require sophisticated high technology equipment is the Balance Error Scoring System (BESS), which has been discussed earlier in this review, due to its cost effective and feasible nature.[67] However, reliability for BESS is only considered moderate, and it also has a significant practice effect along with other limitations discussed earlier.[27-29,31] Nonetheless, it is a feasible and cost effective assessment of acute balance deficits in concussed athletes. Other assessments in balance such as dual-task gait analyses and virtual reality assessments provide useful information about postural control and lingering effects that may not present in the standard clinical balance assessment. They provide a more sensitive measure to detecting subtle changes in postural stability by challenging the systems involved.

Athletes with mild traumatic brain injury have shown acute (first day post injury) balance deficits.[72-75] Research looking at postural stability following concussion found deficits on both the SOT and BESS compared to matched controls on post injury day one.[72] Deficits in dynamic balance control during gait was observed acutely (first testing day) in a population of concussed compared to matched controls.[74] Lastly, research comparing a control group to an experimental soccer heading group (10 headers at 11.2 m/s in 10 minutes) showed significantly higher anterior-posterior and medial-lateral sway values in the experimental group.[73] It is well observed in the literature that in an acutely concussed population balance deficits do exist.

Postural stability usually recovers within 3-5 days following a concussion when performing standard clinical balance assessments.[12,67] However, more sensitive measures, such as static and dynamic balance measures, may indicate deficits that last much longer than 3-5 days.[76,77] In acutely concussed football players, AP center of pressure (COP) displacements were greater than non-concussed, which recovered by return to play (RTP), however COP velocity was elevated compared to controls on RTP day, roughly 26 days after initial injury.[76] Also, altered propulsive and braking forces were observed in gait termination of concussed athletes, despite all participants achieving baseline values on clinical balance assessments.[77] Gait termination may be able to detect lingering motor control strategies in concussed populations.[77]

Using a virtual reality environment has also indicated residual visual motor disintegration and significant balance deficits up to 30 days post injury.[48] These deficits were seen in athletes who had returned to play and were asymptomatic. Concurrent research suggests that motor stability and balance may be impaired up to a month following concussion under divided attention.[78] Individuals are unable to perform simultaneous tasks, such as working memory tasks, without impairments in motor control. Although these athletes had passed basic clinical balance assessments and were "ready" to return to play, they presented altered gait and postural characteristics indicating lingering motor control abnormalities that may affect sport related movements and increase the risk for further injury. The implications of this could be catastrophic, as most athletes have to constantly integrate multiple tasks at once.

Gait characteristics follow a concussion usually consist of attentional deficits, conservative gait strategy, including slower gait velocity, however even with this conservative strategy instability exists as COM deviations in the coronal plane.[79-81] The addition of a cognitive task, such as a working memory task, reveal signs of postural instability and attention deficits in the concussed individuals.[82] Using a question and answer task created the most sensitive measure to distinguish concussed individuals from healthy individuals, and supports the idea of dual task as a more sensitive postural stability assessment.[82] Thus far, the literature suggests gait velocity, and ML-ROM may be more sensitive measures than current clinical assessments and could potentially aid in the assessment of balance and return to play protocol.

A new approach for assessing postural control is a nonlinear dynamic measure known as Approximate Entropy (ApEn). This measure is able to quantify the amount of randomness and irregularity within a time series.[83-85] It is crucial to understand that the human body is comprised of many dynamic non-linear systems as well as physiological rhythms (heartbeat, respiration, sleep wake cycles).[83] Oscillations in postural steadiness could potentially be attributed to the natural rhythms of the postural control system.[83] Therefore research that displays increases in sway indexes or postural steadiness, may not be indicative of abnormal postural control. Approximate Entropy is able to determine the probability that data points within a short sequence are repeated.[83] Healthy adults display COP oscillations that are relatively irregular and small in amplitude while maintaining quiet upright stance, while concussed individuals display more regular oscillations.[83]

ApEn has been useful in detecting subtle changes in postural control, even after the individual demonstrates baseline values of postural stability using common clinical assessments.[84,85] Evaluating concussed individuals compared to their baseline values showed ApEn values for the AP and ML time series declined immediately following injury in individuals with steady and unsteady postural stability.[85] Two to four days later these values remained below baseline, even in athletes who had resolved postural stability.[85] This demonstrates that underlying postural control deficits may exist, disputing the 3-5 day recovery period for postural stability. Similarly, COP data collected from the SOT 48 hours after injury demonstrated COP oscillations that generally became more regular (lower ApEn value) in the concussed population compared to the control.[84] These values were apparent even when athletes displayed normal postural stability, or baseline level. Hence, athletes who displayed “normal” postural stability following concussion still demonstrated subtle changes in postural control. Persistent changes in postural control were observed in athletes who were at least 9 months from initial injury compared to healthy controls.[86] The concussed group had lower COP oscillation randomness and this may indicate chronic effects on postural control. The authors contribute this to a compensatory mechanism to achieve postural stability, such as co-contraction and stiffened lower extremity musculature.

Another theory surrounding regularity within entropy measures takes into account the number of interconnecting systems in a person. With a healthy individual balancing with eyes open, the visual, vestibular, and somatosensory systems are all working together in a complex, highly interconnected fashion, which may produce a more irregular (higher entropy value) output.[87] If fewer components were involved (such as when eyes are closed), all components would contribute to the output, however each component would make a more dominant contribution, and likely produce more regular oscillations.[83] As such, a more regularly order time series would hypothetically be produced by a system with fewer degrees of freedom.[88] Therefore, in the presence of a concussion, where normal interconnections among systems may be compromised, this could in turn reduce the complexity of those connections and produce a more regular time series (entropy) output. This is one model for why more regular entropy values are observed in concussed individuals and more irregular values are observed in healthy controls.

Along with ApEn, Shannon and Renyi entropies have been shown to detect postural instability in athletes nearly 10 days following injury.[89] Interestingly, COP area increases with data length up to two minutes in concussed individuals, therefore at least two minutes is necessary to quantify the effects of concussion on COP area displacement and postural stability. Another form of entropy that is similar to ApEn and Shannon/Renyi entropies is Sample Entropy (SampEn). SampEn appears to be more reliable for shorter data sets, is less sensitive to changes in data length, and has fewer consistency problems than ApEn.[90-92] SampEn has been studied in postural control training, divided attention, differences between Schizophrenia and Depression, and neonatal heart rate variability.[91] However, SampEn has not been explored in the concussion realm, and this gap in the literature may provide insight into regularity of postural control following concussion.

Balance assessments can provide useful information to assess neurologic deficits in athletes following concussion. In some cases, balance impairments only last a few days; however evidence suggest underlying effects may be present but unseen by typical clinical measures of balance. The addition of a cognitive task to a balance assessment could provide a more sensitive measure in the assessment of concussion. Characteristics of gait such as gait velocity, ML-ROM, and gait termination propulsive and braking forces also provide information about alterations in movement strategies and may be more sensitive than current balance assessments. Approximate entropy also shows great promise as a tool to identifying when someone is ready to return to play. Multiple measurements of balance should play a role in the assessment and management of cerebral concussion.

Although there is an abundance of research related to many topics of sport related concussion, a great deal of the research is inconclusive. Unfortunately this type of injury does not produce visible characteristics, such as swelling or bruising that make it obvious to the naked eye, therefore diagnosis and determining recovery becomes difficult. Acute clinical diagnostic tools are effective, however recovery may differ for each individual. A multifaceted approach to concussion assessment would create a more sensitive measure for identifying and treating a concussion. Cumulative effects, although not conclusive, may lead to greater late life deficits and potentially contribute to the manifestation of chronic traumatic encephalopathy. No two concussions are alike, therefore treating them individually, using multiple assessment tools, and progressing the athlete to full recovery is the safest and most effective way to return an athlete to his or her respective sport.

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Appendix C- Tables and Figures

TABLE 1. *Participant demographics, concussion history, and clinical milestones*

Height (cm)	178.3 ± 4.8
Body Mass (kg)	94.0 ± 10.4
Age (years)	20.1 ± 1.6
Previous History (# of concussions)	0.9 ± 1.0 Range: 0-3 previous concussions
Average time to return to play (days)	13.0 ± 5.4 Range: 8 - 27 days
Average time for BESS to return to baseline value (days)	2.4 ± 1.4 Range: 1 - 6 days
Average symptom resolution (days)	5.5 ± 2.8 Range: 2 - 11 days
Sex/Sport	Male/Football

Georgia Southern University

Postural Stability in Individuals following Concussion

A. Demographic Data

(1) Subject Date of Birth: ____ /____/ ______

(2) Age: ________ (3) Gender: _________

(4) Year in School: Freshman Sophomore Junior Senior 5th Year

B. Injury History

(1) When did you suffer your concussion? ______/ ______/ ______

(2) When you suffered <u>this</u> concussion, do you experience the following?

(a) Loss of Consciousness Yes No

(b) Amnesia (Memory Loss) Yes No

(3) Which symptom has been most troubling in the last 24 hours?

____

(4) Have you ever suffered a concussion before? Yes No

If Yes, how many? ____________

If Yes, when was your more recent concussion before this one? ____________

(5) Have you ever been knocked out while playing your sport? Yes No

If Yes, how many times has this happened? ____________

(6) Have you ever had your "bell rung" or "dinged" following a hit to the head while playing your sport? Yes No

If Yes, has it happened this season? Yes No

Has this happened to you in a prior season? Yes No

(7) Have you ever been hit in the head while playing your sport and suffered from 2 or more of the following (see list on page 2) Yes No

If Yes, has it happened this season? Yes No

If Yes, how many times this season? ___________________

Has this happened to you in a prior season? Yes No

(8) Have you ever been diagnosed with;

(a) A balance disorder? Yes No

(b) Metabolic disorder? Yes No

(c) Neurological Disorder? Yes No

(d) Vestibular Disorder? Yes No

(9) Are you currently taking any medications? Yes No

<u>If Yes on #8 or #9, please describe the condition/medication and when you were diagnosed:</u>

____

____

____

FIGURE 1—Health History Questionnaire

Table 1

Graduated return to play protocol

Rehabilitation stage	Functional exercise at each stage of rehabilitation	Objective of each stage
1. No activity	Symptom limited physical and cognitive rest	Recovery
2. Light aerobic exercise	Walking, swimming or stationary cycling keeping intensity <70% maximum permitted heart rate No resistance training	Increase HR
3. Sport-specific exercise	Skating drills in ice hockey, running drills in soccer. No head impact activities	Add movement
4. Non-contact training drills	Progression to more complex training drills, eg, passing drills in football and ice hockey May start progressive resistance training	Exercise, coordination and cognitive load
5. Full-contact practice	Following medical clearance participate in normal training activities	Restore confidence and assess functional skills by coaching staff
6. Return to play	Normal game play	

***FIGURE 2*—**Graduated Return to Play Protocol from the 4th CIS

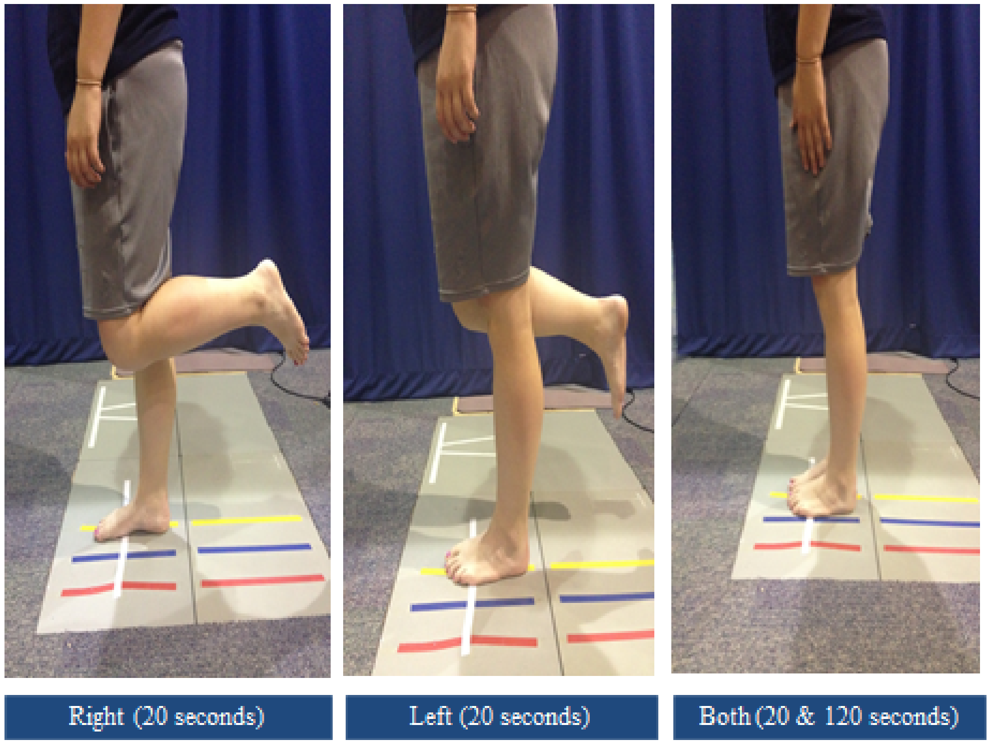

FIGURE 3—Quiet stance postural stability protocol

TABLE 2. *P-values for the comparison of each average leg condition across testing days*

95% Area	Right	Left	Both 120 s	Both 20 s
Right	-	0.175	0.999	0.000*
Left		-	0.128	0.000*
Both 120 s			-	0.000*
Vavg	Right	Left	Both 120 s	Both 20 s
Right	-	0.885	0.000*	0.000*
Left		-	0.000*	0.000*
Both 120 s			-	0.999
ApEn AP	Right	Left	Both 120 s	Both 20 s
Right	-	0.964	0.000*	0.000*
Left		-	0.000*	0.000*
Both 120 s			-	0.002*
ApEn ML	Right	Left	Both 120 s	Both 20 s
Right	-	0.343	0.000*	0.000*
Left		-	0.000*	0.000*
Both 120 s			-	1.000
SampEn AP	Right	Left	Both 120 s	Both 20 s
Right	-	0.780	0.000*	0.000*
Left		-	0.000*	0.000*
Both 120 s			-	0.000*
SampEn ML	Right	Left	Both 120 s	Both 20 s
Right	-	0.704	0.000*	0.000*
Left		-	0.000*	0.000*
Both 120 s			-	0.024*

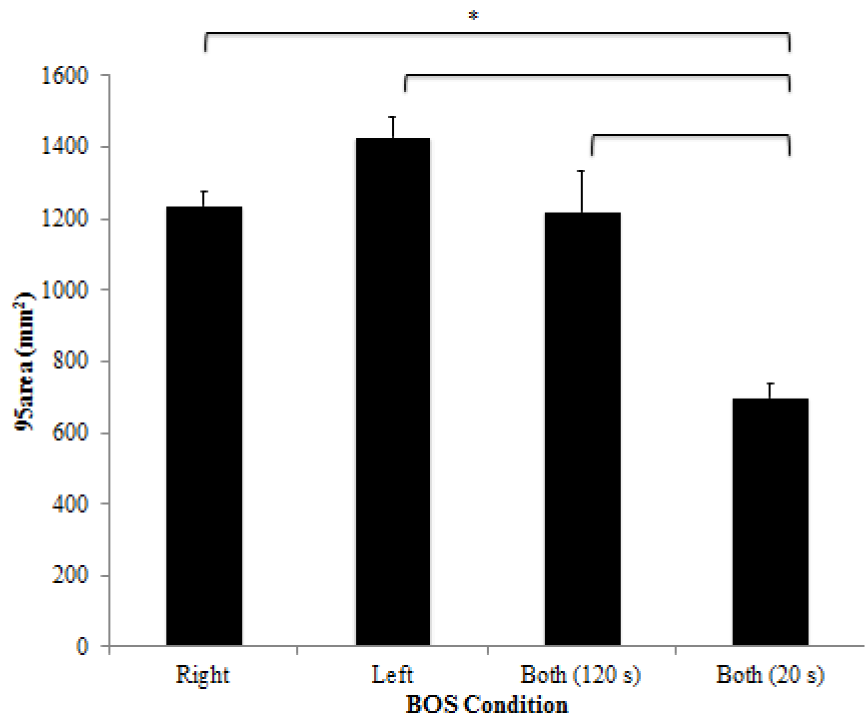

***FIGURE 4*—**Ninety-five percent area average across days compared amongst different leg conditions. *indicates significant difference between BOS conditions

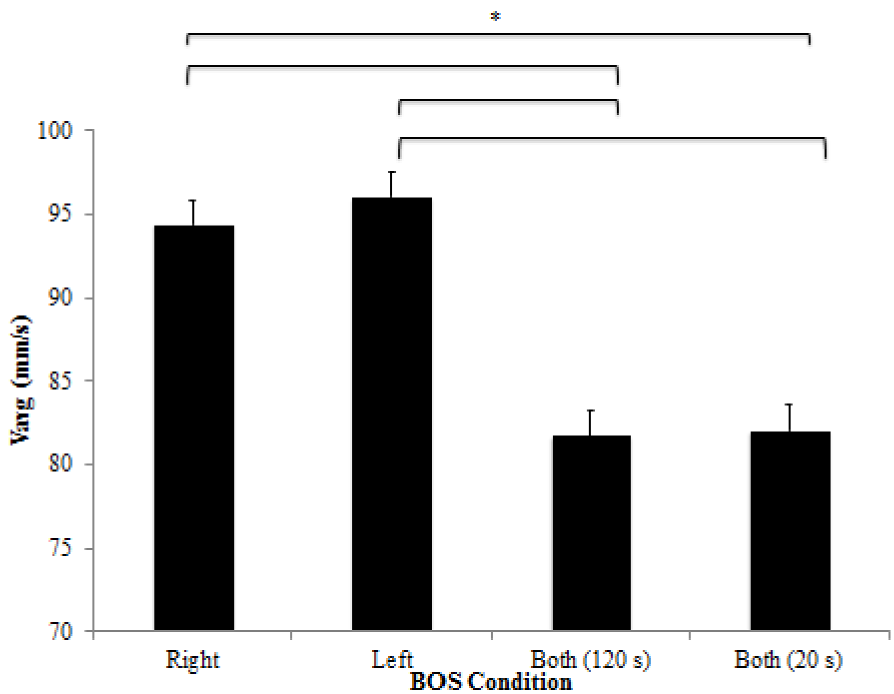

FIGURE 5— Average velocity mean across days compared amongst different leg conditions. *indicates significant difference between BOS conditions

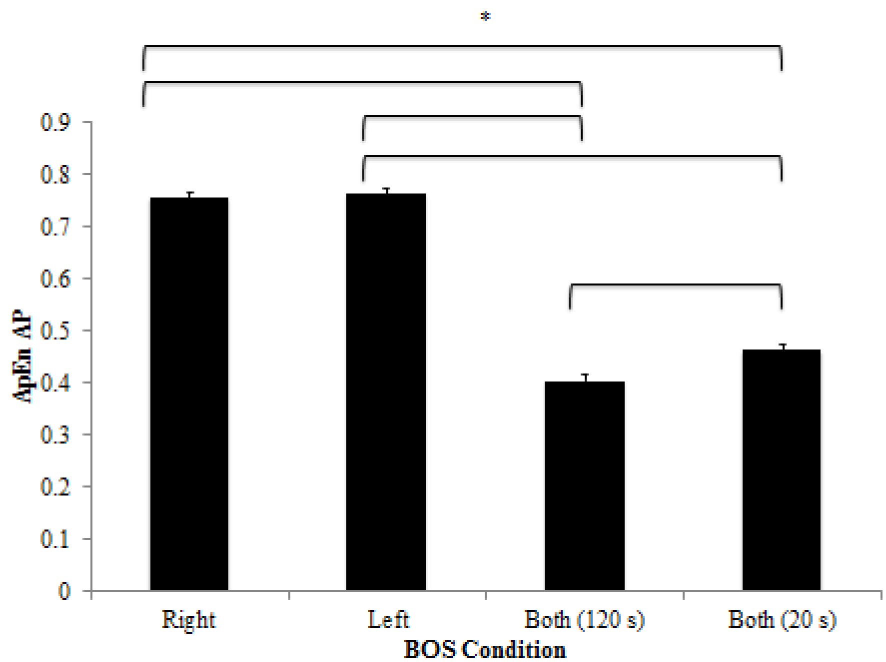

FIGURE 6—Average approximate entropy across testing days in the AP direction amongst leg conditions. *indicates significant difference between BOS conditions

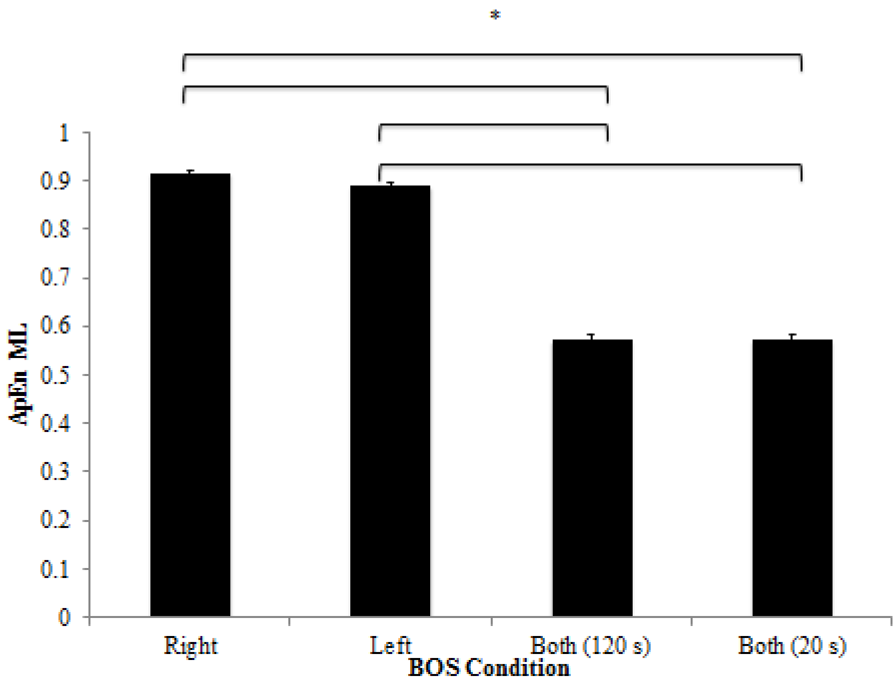

FIGURE 7— Average approximate entropy across testing days in the ML direction amongst leg conditions. *indicates significant difference between BOS conditions

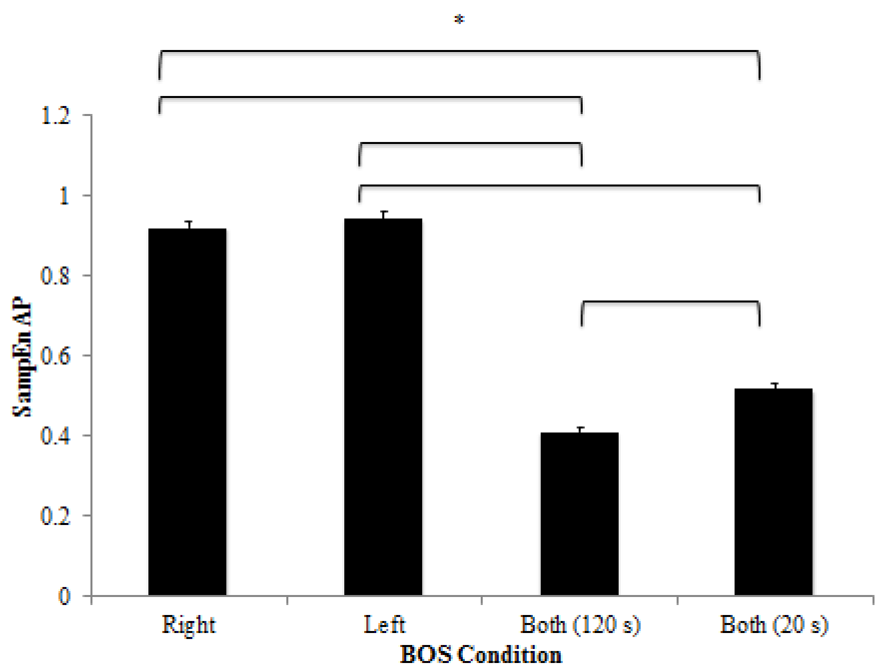

FIGURE 8—Average sample entropy across testing days in the AP direction amongst leg conditions. *indicates significant difference between BOS conditions

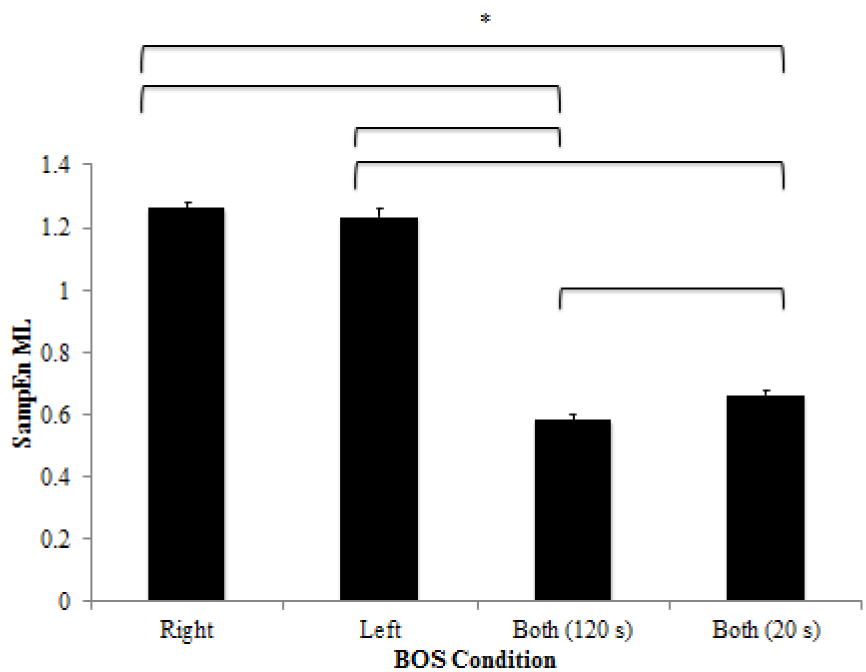

FIGURE 9—Average sample entropy across testing dates in the ML direction amongst leg conditions. *indicates significant difference between BOS conditions