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Postural Control and Head Impact Exposure in Youth Football Players: Comparison of the Balance Error Scoring System and a Force Plate Protocol

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Abstract

Postural control testing is often used by clinicians and athletic trainers to assess the health of athletes during recovery from a concussion. Characterization of postural control as a clinical tool for use with youth athletes is limited though. The objective of this study was to compare performance on the Balance Error Scoring System (BESS) and a force plate protocol at the beginning and end of a season of football within a cohort of 34 healthy youth football players (average age of 9.9 ± 0.6 years). A secondary aim was to investigate if changes in measures of balance from the postseason to the preseason were correlated with head impact exposure. Players completed testing at the beginning and end of the youth football season. There were no significant differences between BESS scores before the season and after the season ($p = 0.54$). Performance on the BESS was not associated with any of the center of pressure (COP) metrics considered in this study. No correlation was observed between measures of balance and head impact exposure for the season. Further research is required to determine the viability of postural control testing with this population.

Keywords

Balance; Pediatrics; Concussion

INTRODUCTION

Sports-related concussions have become a public health concern, with as many as 3.8 million occurring annually in the United States.^{1–3} Biomechanics research regarding football-related concussions has been spurred by data showing football to have the highest concussion incidence.⁴ Despite the fact that youth players constitute 70% of the football-playing population, most research has focused on high school and older populations^{5–9} rather than youth populations.^{10–12}

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Athletes who have suffered a concussion can experience changes in postural control, as concussions interfere with the nervous system.^{13,14} In collegiate populations, short-term learning impairments and balance deficits have been observed even for non-concussed players.^{15,16} Following exposure to head impacts, the most commonly implemented balance testing protocol used by healthcare providers in the care of athletes in assessing postural control in athletes is the Balance Error Scoring System (BESS).¹³ The BESS is a clinical, static balance assessment that is easy to administer and may be used without instrumented testing devices.¹⁷ The BESS testing protocol is described in the methods section of this manuscript. It has primarily been used to measure postconcussion deficits from sports injuries, though it was initially developed as a sideline tool.^{13,17–20} The BESS has even been shown to differentiate between concussed and healthy youth athletes.^{17,21} The reliability of the overall BESS has been shown to vary considerably, while a modified version has shown improved results.^{17,20–25} Utilization of repeated administration to increase the reliability of the protocol is not recommended as a practice effect has been observed for repeated tests of the BESS, though the magnitude of this practice effect is variable.²⁶

Alternatively, a static balance assessment on a force plate consisting of eyes open and eyes closed trials have been used to assess athlete postural control.^{20,27–36} These protocols typically track center of pressure trajectories to characterize balance. This quantitative analysis of balance has been used to delineate between healthy and impaired states for athletes.^{27,28,33}

Though both the BESS and force plate protocols have been used extensively in assessing postural control of both healthy and impaired athletes, assessment of the protocols has been limited at the youth level. Youth males have been shown to develop postural control later in adolescence, necessitating analysis of commonly used postural control testing protocols.^{35,37} The objective of this study was to compare performance on the Balance Error Scoring System (BESS) and a force plate protocol at the beginning and end of a season of football within a cohort of 34 youth football players (average age of 9.9 ± 0.6 years) and relate temporal changes in performance to head impact exposure. Evaluation of these protocols in the youth population should be conducted prior to their implementation and may prompt development of youth-specific postural control testing.

METHODS

Two teams of 9–11 year old youth football players (average age of 9.9 ± 0.6 years) comprised the subjects for this study approved by the Virginia Tech Institutional Review Board. Players were recruited and provided verbal assent to participation while their guardians provided written consent. Preseason testing was conducted the first week of the season before contact practice began and postseason testing was completed within 2 weeks of the end of the season. The testing consisted of BESS administration and a force platform protocol. Subjects were tested individually in a closed environment. All testing was conducted by lab personnel who were trained on the BESS and the determination of what constitutes an error in order to limit tester bias. Preseason testing was completed by 34 players, of which 31 completed postseason testing. One player's testing data was not used as the athlete had a neurological condition (Attention Deficit Hyperactivity Disorder) that could

affect postural control.³⁸ Subject injury history data were collected to determine whether any subject balance data should be excluded on the basis of a previous lower extremity or back injury. No players in this study were excluded based on this criterion. Analysis only considered the 30 players that completed testing at the beginning and end of the season. No player was diagnosed with a concussion during the course of the season.

The BESS utilizes three stances: double leg, single leg, and tandem that are tested on both a flat surface and a foam pad (Airex Balance Pad 81000, Power Systems, Knoxville, Tennessee). This represents a total of six trials, each of which has a 20 second duration and is conducted with the participant's eyes closed with a hand placed on each hip.²⁰ A subscore for each trial is determined by counting participant errors, with an overall score representing the summation of each trial's score. Errors included opening of the eyes, stepping or falling, removing hands from the hips, abduction or flexion of the hip beyond 30°, lifting of the heel or toes from the testing surface, and failure to return to testing position within five seconds. Simultaneous errors are counted as one overall error. The maximum possible subscore is ten. Lower scores on the BESS are associated with better postural control.

Center of pressure (COP) data were collected using an IsoBALANCE®2.0 (IsoTechnology, Australia) force plate. Participants completed two 30 second trials – one with eyes open and the other with eyes closed.²⁸ Foot placement was consistent among all participants with indicators on the platform. Subjects were directed to place the feet on the outside of two lines on the force plate and stand up straight. Testing commenced when the subject's COP was positioned in the center of the force plate, which was observable in real-time. The force plate output COP trajectories at a frequency of approximately 10 Hz in x and y coordinates over the course of the test. The x-axis represents the Medial-Lateral (ML) axis while the y-axis represents the Anterior-Posterior (AP) axis. Similarly to Quatman-Yates et al.,³³ a distinction was made between COP measures of path characteristics and data structure characteristics. Path characteristics are metrics that represent the spatial variability of the data, while data structure characteristics capture patterns of temporal variability within the data. Path characteristics have been summarized in Table 1. Path characteristic metrics are inherently similar, which can make it difficult to differentiate among the various metrics.^{27,33}

Recently, various measures of the entropy of the COP trajectory have been utilized to further characterize the postural data.^{29,33,34,39–41} Entropy measures the overall variability or randomness of a particular data series and is considered as a data structure characteristic. A lower entropy value would be indicative of a less varied balance trajectory. This dual approach, including both path and data structure characteristics, provides an overall description of the postural stability of each participant. Four measures of data entropy were generated for each test: AP, ML, Renyi, and Shannon Entropy.^{28,34,39,42}

AP and ML Entropy are calculations of sample entropy and represent the variability of the COP trajectory as it relates to each direction respectively. Sample entropy is determined by comparing a given data vector template from the COP trajectory to all other vectors within the trajectory and counts all those that are within a defined similarity range. A more comprehensive description regarding the algorithm for determining sample entropy is

available.^{40,43} Parameter selection for this analysis was conducted as specified by Lake et al.⁴²

Renyi and Shannon Entropy represent variability in the overall COP trajectory and are determined through graphical representation of the trajectory. A grid is developed that contains subunits that are equal in length and height to the standard deviation in the ML and AP directions respectively. Then, the number of points in the trajectory found within each subunit are determined in order to calculate the probability of COP coordinates residing in a particular subunit. Using this probability, Shannon Entropy is defined as follows:

$$\text{Shannon Entropy} = - \sum_{i=1}^m p_i \ln p_i$$

where p_i represents the probability of COP coordinates residing in a specific subunit of the m overall subunits.³⁹ A data set that resides entirely within a single subunit would intuitively result in a Shannon Entropy of 0. Renyi Entropy represents the generalized form of Shannon Entropy and utilizes the same methodology. It is calculated as follows:

$$\text{Renyi Entropy} = \frac{1}{1-q} \ln \left(\sum_{i=1}^m p_i^q \right)$$

where q is a selected parameter and is equal to -1 for this analysis.³³

Head impact data were collected through the use of helmets instrumented with accelerometer arrays (Head Impact Telemetry [HIT] System, Simbex, Lebanon, NH). The HIT System consists of an array of six accelerometers that are mounted inside of Riddell Revolution or Speed helmets and record acceleration data whenever an individual data channel exceeded a 14.4 g threshold. In order to distinguish between actual impacts and accelerations that could be associated with running or jumping, a 10 g resultant acceleration threshold is further used. For this study, season head impact exposure was defined as the number of head impacts a player experienced between preseason and postseason testing. No subject completed preseason testing after contact was initiated or postseason testing prior to the conclusion of the season.

Coefficients of determinations were calculated for individual trials of the BESS to determine how predictive each stance was of the overall score. This same calculation was carried out for path characteristics and data structure characteristics for the force plate protocol to determine whether any one metric was more predictive than another. Differences between preseason and postseason data, as well as eyes open and eyes closed force plate data, were assessed using paired t-tests with a level of significance defined for $\alpha < 0.05$. Comparisons between the two protocols were then conducted to determine if there was any correlation between the different stances of the BESS and the various balance measures of the force plate protocol. Lastly, changes in balance measures from the postseason relative to the preseason were related to head impact exposure to determine whether a season of youth football was correlated with changes in these outcomes.

RESULTS

The BESS protocol detected no significant difference between preseason and postseason testing for the overall score ($p = .54$). Both two-foot tests resulted in very few errors while the one-foot test conducted on a foam surface resulted in a large amount of errors for most participants (Figure 1). Further, these 3 stances explained low amounts of variance in the overall score (R^2 values below 0.36). The one-foot test conducted on a flat surface was found to be most correlated to the overall score (Table 2). Though no overall differences were observed between preseason (Total score: 16.9 ± 5.7 errors; Range: 9–27) and postseason BESS scores (Total score: 18.5 ± 6.1 errors; Range: 7–27), individual athletes' scores varied (Figure 2).

The force plate protocol consisted of two trials (eyes open and eyes closed) and two time points (preseason and postseason). The average and standard deviation for each metric is reported in Table 3. The eyes open and eyes closed trials were found to be significantly different for AP and ML Entropy, as well as each of the path characteristics except for ML Sway ($p < 0.05$). Greater subject variability was observed in the eyes closed trial than in the eyes open trial (Figure 3). Similar to the BESS, preseason and postseason data were not significantly different ($p > 0.05$). Individual variances, both negative and positive, for athletes between preseason and postseason tests were present. Some athletes performed better in the preseason than in the postseason while others experienced the opposite effect.

Since differences between preseason and postseason testing for both the BESS and force plate protocol were not observed, the data were combined into one pool for the purposes of assessing the correlation of the BESS and force plate metrics. Distinction was made between eyes open and eyes closed trials in assessing correlation between the two testing protocols. The number of errors for each trial of the BESS was compared to both path and data structure characteristics from the force plate protocol to determine correlation. No correlation between the test methods was observed (R^2 values ranged from 0–0.1).

To determine the effect of a season of football on measures of balance, the overall number of head impacts experienced during the season was compared to changes in force plate metrics and scores on the BESS (Figure 4). The average number of head impacts experienced by a player was 197 ± 159 , with a maximum number of head impacts of 705. No correlation between increased head impact exposure and change in performance on postural control testing was observed (R^2 values < 0.1).

DISCUSSION

The average number of total BESS errors reported in this study was greater than that reported in adult populations.¹⁷ Both of the two foot trials resulted in less than one error on average (Figure 1). These trials were not challenging enough for the participants in this study. A modified BESS protocol has been previously presented that eliminates the use of the two footed trials, though it has not been applied to youth populations.²⁴ We further analyzed results by eliminating the these two-foot trials as they were associated with low variance, not inversely tied to exertion or fatigue, and were found to not differentiate

concussed and healthy athletes.^{20,26,44,45} The one foot trial performed on a foam pad resulted in the highest average error (5.9 ± 1.5) among all trials and was consistent with previous research.^{20,21} Athletes struggled to maintain balance throughout the trial. In select cases, athletes took extended periods of time to return to the testing stance, leading to fewer errors. Considering the limited variance between subjects on each of the two foot trials and the one foot trial on a foam pad, we hypothesize that a youth-specific BESS administration may be necessary, though the overall validity of the BESS for use within a youth population was not assessed in this study. These trials were observed to have the greatest variance among this healthy cohort of youth football players. For valid assessments, stances with greater variance between subjects would be expected to be better indicators of postural control both between and within subjects. For an athlete with a concussion, it has been shown that performance on the BESS has worsened for a period of time following the injury.^{13,18,19,24,46}

The force plate protocol confirmed a difference between the eyes open and eyes closed tests in terms of path characteristics. This is consistent with previous findings.²⁸ Most athletes performed well in the eyes open test while greater disparity between subjects was observed during the eyes closed test (Figure 3). Selection of an optimal path metric for assessment of postural control is confounded by the fact that the metrics in this study are defined by some of the same variables. For instance, the 95% confidence ellipse area is calculated by using the sway in the anterior-posterior and medial-lateral directions, which would lead to highly correlated measures. No path metric is recommended over another for this testing protocol. Other studies have shown various entropy measurements to differentiate postural control in youth populations.^{28,33,39} These studies utilized the eyes open and eyes closed protocol from this study but for a two minute duration instead of the 30 seconds implemented here. The two minute duration has been observed to maximize the detection of COP changes due to concussion.³⁹ This longer duration test could also potentially result in measurements of non-stable COP trajectories that would prevent use of the path characteristic metrics presented in this study, though entropy measurements may still be viable.³⁰ It has also been shown that the resultant entropy vector heading may be an effective differentiator of postural control, more so than entropy along the AP or ML directions.⁴⁷

Although it has been posited that repetitive subconcussive head impacts may lead to transient changes in balance, that trend was not exhibited within this cohort of youth football players (Figure 4). For both the BESS and force plate protocols, no overall differences between preseason and postseason data were observed. Further, no correlation was observed between changes in measures of balance and head impact exposure. Some players who experienced a small number of head impacts on the season performed worse at the end of the season than at the beginning while players with a high number of head impacts improved in balance measures. As young males are still developing postural control through adolescence, the balance measures employed in this study may not be effectively capturing differences in balance. Individual athletes exhibited differences between the two test sessions. These differences could stem from improved balance due to consistent physical activity (i.e. a season of football), or transient effects like fatigue or learning effects.^{16,23,25,26,44,45}

No subjects in this study experienced a diagnosed concussion so the effectiveness of the BESS and a force plate protocol could not be characterized. The reliability of the BESS in adult populations has been shown previously to vary.¹⁷ Further, postural control development in youth populations, specifically males, is limited.^{35,48,49} Thus, differences in BESS scores among athletes may be more indicative of developmental differences, both neurologic and physiologic, than of postural control differences. The BESS is limited by a scoring sensitivity that can fail to differentiate subjects with varied levels of postural control.⁵⁰ Lab personnel were trained in the scoring of the BESS in order to limit tester bias, though independent scoring would have minimized any bias. A need for a youth-specific modified BESS protocol is suggested, however the clinical validity of the BESS within a youth population remains uncertain. As studies have shown concussed, adult athletes to demonstrate poorer balance than their healthy counterparts, a youth-specific BESS could also increase the efficacy of the test in youth populations. Further, a limited force plate protocol was utilized in this study. The 30 second trials used in this study may not fully capture some low frequency changes that have been observed to occur in longer duration trials.⁵¹ Though the force plate sampling rate used in this study was low compared to other similar studies, it has been reported previously that 95% of the COP trajectory magnitude is less than 2 Hz and more than 99% is below 10 Hz.^{47,52,53}

Two youth football teams of players 9–11 years old completed preseason and postseason postural control testing that consisted of administration of the BESS and a force plate protocol. The data suggest that there is a need for a youth-specific modified BESS test. Path and data structure characteristics may both be effective in assessing postural control within this population but the test duration and positioning must be considered. The measures of balance used in this study were not observed to relate to head impact exposure. The use of postural control testing in a youth population may be viable, though further research exploring the effectiveness of these protocols is necessary.

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References

1. CDC. Nonfatal traumatic brain injuries related to sports and recreation activities among persons aged 19 years — United States, 2001–2009. MMWR: Morbidity and mortality weekly report. 2011; 60(39):1337–1342. [PubMed: 21976115]
2. Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. The Journal of head trauma rehabilitation. 2006; 21(5):375–378. [PubMed: 16983222]
3. Stern RA, Riley DO, Daneshvar DH, Nowinski CJ, Cantu RC, McKee AC. Long-term consequences of repetitive brain trauma: chronic traumatic encephalopathy. PM R. 2011; 3(10 Suppl 2):S460–467. [PubMed: 22035690]
4. Gessel LM, Collins CL, Dick RW. Concussions among United States high school and collegiate athletes. Journal of athletic training. 2007; 42(4):495. [PubMed: 18174937]

5. Broglio SP, Surma T, Ashton-Miller JA. High school and collegiate football athlete concussions: a biomechanical review. *Ann Biomed Eng.* 2012; 40(1):37–46. [PubMed: 21994058]
6. Crisco JJ, Wilcox BJ, Beckwith JG, et al. Head impact exposure in collegiate football players. *J Biomech.* 2011; 44(15):2673–2678. [PubMed: 21872862]
7. Mihalik JP, Bell DR, Marshall SW, Guskiewicz KM. Measurement of head impacts in collegiate football players: an investigation of positional and event-type differences. *Neurosurgery.* 2007; 61(6):1229–1235. discussion 1235. [PubMed: 18162902]
8. Pellman EJ, Viano DC, Tucker AM, Casson IR, Waeckerle JF. Concussion in professional football: reconstruction of game impacts and injuries. *Neurosurgery.* 2003; 53(4):799–812. discussion 812–794. [PubMed: 14519212]
9. Rowson S, Brolinson G, Goforth M, Dietter D, Duma SM. Linear and angular head acceleration measurements in collegiate football. *J Biomech Eng.* 2009; 131(6):061016. [PubMed: 19449970]
10. Cobb BR, Urban JE, Davenport EM, et al. Head impact exposure in youth football: elementary school ages 9–12 years and the effect of practice structure. *Ann Biomed Eng.* 2013; 41(12):2463–2473. [PubMed: 23881111]
11. Daniel RW, Rowson S, Duma SM. Head Impact Exposure in Youth Football. *Ann Biomed Eng.* 2012; 40(4):976–981. [PubMed: 22350665]
12. Urban JE, Davenport EM, Golman AJ, et al. Head Impact Exposure in Youth Football: High School Ages 14 to 18 Years and Cumulative Impact Analysis. *Ann Biomed Eng.* 2013
13. Guskiewicz KM. Balance assessment in the management of sport-related concussion. *Clinics in sports medicine.* 2011; 30(1):89–102. [PubMed: 21074084]
14. McCrory P, Meeuwisse W, Aubry M, et al. Consensus statement on concussion in sport—the 4th International Conference on Concussion in Sport held in Zurich, November 2012. *Clin J Sport Med.* 2013; 23(2):89–117. [PubMed: 23478784]
15. McAllister TW, Flashman LA, Maerlender A, et al. Cognitive effects of one season of head impacts in a cohort of collegiate contact sport athletes. *Neurology.* 2012; 78(22):1777–1784. [PubMed: 22592370]
16. Mulligan I, Boland M, Payette J. Prevalence of neurocognitive and balance deficits in collegiate football players without clinically diagnosed concussion. *Journal of orthopaedic & sports physical therapy.* 2012; 42(7):625–632. [PubMed: 22531476]
17. Bell DR, Guskiewicz KM, Clark MA, Padua DA. Systematic review of the balance error scoring system. *Sports Health: A multidisciplinary approach.* 2011; 3(3):287–295.
18. Broglio SP, Puetz TW. The effect of sport concussion on neurocognitive function, self-report symptoms and postural control. *Sports Medicine.* 2008; 38(1):53–67. [PubMed: 18081367]
19. McCrear M, Guskiewicz K, Marshall S, et al. Acute effects and recovery time following concussion in collegiate football players. *Sports Med Update.* 2004; 38:369–371.
20. Riemann BL, Guskiewicz KM, Shields EW. Relationship between clinical and forceplate measures of postural stability. *Journal of Sport Rehabilitation.* 1999; 8:71–82.
21. Furman GR, Lin C-C, Bellanca JL, Marchetti GF, Collins MW, Whitney SL. Comparison of the balance accelerometer measure and balance error scoring system in adolescent concussions in sports. *The American journal of sports medicine.* 2013; 41(6):1404–1410. [PubMed: 23585486]
22. Broglio SP, Zhu W, Sopiarz K, Park Y. Generalizability theory analysis of balance error scoring system reliability in healthy young adults. *Journal of athletic training.* 2009; 44(5):497–502. [PubMed: 19771288]
23. McLeod TCV, Perrin DH, Guskiewicz KM, Shultz SJ, Diamond R, Gansneder BM. Serial administration of clinical concussion assessments and learning effects in healthy young athletes. *Clinical Journal of Sport Medicine.* 2004; 14(5):287–295. [PubMed: 15377968]
24. Hunt TN, Ferrara MS, Bornstein RA, Baumgartner TA. The reliability of the modified balance error scoring system. *Clinical Journal of Sport Medicine.* 2009; 19(6):471–475. [PubMed: 19898074]
25. Hrysomallis C. Balance ability and athletic performance. *Sports medicine.* 2011; 41(3):221–232. [PubMed: 21395364]

26. Valovich TC, Perrin DH, Gansneder BM. Repeat administration elicits a practice effect with the Balance Error Scoring System but not with the Standardized Assessment of Concussion in high school athletes. *Journal of Athletic Training*. 2003; 38(1):51. [PubMed: 12937472]
27. Cavanaugh JT, Guskiewicz KM, Giuliani C, Marshall S, Mercer V, Stergiou N. Detecting altered postural control after cerebral concussion in athletes with normal postural stability. *British journal of sports medicine*. 2005; 39(11):805–811. [PubMed: 16244188]
28. Cavanaugh JT, Guskiewicz KM, Giuliani C, Marshall S, Mercer VS, Stergiou N. Recovery of postural control after cerebral concussion: new insights using approximate entropy. 2006
29. Fino PC, Mojdehi AR, Adjerid K, Habibi M, Lockhart TE, Ross SD. Comparing postural stability entropy analyses to differentiate fallers and non-fallers. *Annals of biomedical engineering*. 2015;1–10. [PubMed: 25527321]
30. Kim G, Ferdjallah M, Harris GF. Fast computational analysis of sway area using center of pressure data in normal children and children with cerebral palsy. *American Journal of Biomedical Sciences*. 2009; 1(4):364–372.
31. Mochizuki L, Duarte M, Amadio AC, Zatsiorsky VM, Latash ML. Changes in postural sway and its fractions in conditions of postural instability. *Journal of Applied Biomechanics*. 2006; 22(1):51. [PubMed: 16760567]
32. Moghadam M, Ashayeri H, Salavati M, et al. Reliability of center of pressure measures of postural stability in healthy older adults: effects of postural task difficulty and cognitive load. *Gait & Posture*. 2011; 33(4):651–655. [PubMed: 21458272]
33. Quatman-Yates CC, Bonnette S, Hugentobler JA, et al. Postconcussion postural sway variability changes in youth: the benefit of structural variability analyses. *Pediatric physical therapy*. 2015; 27(4):316–327. [PubMed: 26397071]
34. Ramdani S, Seigle B, Lagarde J, Bouchara F, Bernard PL. On the use of sample entropy to analyze human postural sway data. *Medical engineering & physics*. 2009; 31(8):1023–1031. [PubMed: 19608447]
35. Smith A, Ulmer F, Wong D. Gender differences in postural stability among children. *Journal of human kinetics*. 2012; 33:25–32. [PubMed: 23487417]
36. Zech A, Klahn P, Hoeft J, Zu Eulenburg C, Steib S. Time course and dimensions of postural control changes following neuromuscular training in youth field hockey athletes. *European journal of applied physiology*. 2014; 114(2):395–403. [PubMed: 24318788]
37. Riach CL, Starkes JL. Velocity of centre of pressure excursions as an indicator of postural control systems in children. *Gait & Posture*. 1994; 2(3):167–172.
38. Shorer Z, Becker B, Jacobi-Polishook T, Oddsson L, Melzer I. Postural control among children with and without attention deficit hyperactivity disorder in single and dual conditions. *European journal of pediatrics*. 2012; 171(7):1087–1094. [PubMed: 22350284]
39. Gao J, Hu J, Buckley T, White K, Hass C. Shannon and Renyi entropies to classify effects of mild traumatic brain injury on postural sway. *PLoS One*. 2011; 6(9):e24446. [PubMed: 21931720]
40. Kuznetsov N, Bonnette S, Riley MA. Nonlinear time series methods for analysing behavioural sequences. *Complex Systems in Sport*. 2014:346.
41. Ramdani S, Seigle B, Varoqui D, Bouchara F, Blain H, Bernard PL. Characterizing the dynamics of postural sway in humans using smoothness and regularity measures. *Annals of biomedical engineering*. 2011; 39(1):161–171. [PubMed: 20686923]
42. Lake DE, Richman JS, Griffin MP, Moorman JR. Sample entropy analysis of neonatal heart rate variability. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*. 2002; 283(3):R789–R797.
43. Richman JS, Moorman JR. Physiological time-series analysis using approximate entropy and sample entropy. *American Journal of Physiology-Heart and Circulatory Physiology*. 2000; 278(6):H2039–H2049. [PubMed: 10843903]
44. Susco TM, McLeod TCV, Gansneder BM, Shultz SJ. Balance recovers within 20 minutes after exertion as measured by the Balance Error Scoring System. *Journal of athletic training*. 2004; 39(3)
45. Wilkins JC, McLeod TCV, Perrin DH, Gansneder BM. Performance on the balance error scoring system decreases after fatigue. *Journal of athletic training*. 2004; 39(2):156. [PubMed: 15173867]

46. Schmidt JD, Register-Mihalik JK, Mihalik JP, Kerr ZY, Guskiewicz KM. Identifying impairments after concussion: normative data versus individualized baselines. *Med Sci Sports Exerc.* 2012; 44(9):1621–1628. [PubMed: 22525765]
47. Rhea CK, Kiefer AW, Haran FJ, Glass SM, Warren WH. A new measure of the CoP trajectory in postural sway: Dynamics of heading change. *Medical engineering & physics.* 2014; 36(11):1473–1479. % @ 1350–4533. [PubMed: 25189142]
48. Geldhof E, Cardon G, De Bourdeaudhuij I, et al. Static and dynamic standing balance: test-retest reliability and reference values in 9 to 10 year old children. *European journal of pediatrics.* 2006; 165(11):779–786. [PubMed: 16738867]
49. Nolan L, Grigorenko A, Thorstensson A. Balance control: sex and age differences in 9-to 16-year-olds. *Developmental Medicine & Child Neurology.* 2005; 47(07):449–454. [PubMed: 15991864]
50. Mulligan IJ, Boland MA, McIlhenny CV. The balance error scoring system learned response among young adults. *Sports health.* 2013; 5(1):22–26. [PubMed: 24381697]
51. Carpenter MG, Frank JS, Winter DA, Peysar GW. Sampling duration effects on centre of pressure summary measures. *Gait & posture.* 2001; 13(1):35–40. % @ 0966–6362. [PubMed: 11166552]
52. Maurer C, Peterka RJ. A new interpretation of spontaneous sway measures based on a simple model of human postural control. *Journal of Neurophysiology.* 2005; 93(1):189–200. [PubMed: 15331614]
53. Prieto TE, Myklebust J, Hoffmann R, Lovett E, Myklebust B. Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Transactions on biomedical engineering.* 1996; 43(9):956–966. [PubMed: 9214811]

Figure 1.

Two foot stances resulted in minimal errors while the one foot test performed on foam had a median of five errors. Greater variability was observed for both tandem stances, as well as the one foot stance on a flat surface. The line in the middle of each box denotes the median; boxes represent the interquartile range; and plus signs denote the outliers. The whiskers represent the threshold for points being designated as outliers. The whiskers are defined to be 1.5 times the interquartile range from the first or third quartile. If a boxplot does not have an outlier, then the whiskers represent the minimum or maximum.

Figure 2. Preseason and postseason BESS scores were found to not differ. Individual subject variability was present.

Figure 3. Subjects generally performed well during the eyes open trial. Lower performances and greater subject disparity were observed during the eyes closed trial.

Figure 4. Representative correlation between head impact exposure and changes in measures of balance. Neither the BESS nor the force plate protocol were observed to correlate with head impact exposure. Negative changes would present the postseason score being lower than the preseason score, which would indicate improved measures of balance. No measure of balance was associated with an R^2 value greater than 0.1.

Table 1

Summary of path characteristics and method of calculation.

Metric	Description	Equation
<i>Sway AP</i>	Standard deviation of movement in AP direction	$S_{AP} = \sqrt{\frac{\sum_{i=1}^N (AP_i - \overline{AP})^2}{N-1}}$
<i>Sway ML</i>	Standard deviation of movement in ML direction	$S_{ML} = \sqrt{\frac{\sum_{i=1}^N (ML_i - \overline{ML})^2}{N-1}}$
<i>Path Length</i>	Total distance traveled during trial	$PL = \sum_{i=2}^N \sqrt{(AP_i - AP_{i-1})^2 + (ML_i - ML_{i-1})^2}$
<i>Maximum Path Velocity</i>	Max velocity during trial	$MPV = \frac{\sum_{i=1}^N (PL_{i+1} - PL_i)}{t_{i+1} - t_i}$
<i>COP Area</i>	95% confidence ellipse area	$2\pi F_{.05, 2, N-2} (S_{AP}^2 S_{ML}^2 - S_{AP-ML}^2)$ S_{AP-ML} is the covariance between the AP and ML directions.

Table 2

R^2 values against total score were observed to be lowest for the two foot stances. Though the tandem flat and one foot foamtests had the same R^2 value, greater variability was observed in the tandem flat stance.

<i>Coefficients of Determination Relative to Total Score</i>		
<i>Flat</i>	Two Foot	0.00
	One Foot	0.61
	Tandem	0.36
<i>Foam</i>	Two Foot	0.24
	One Foot	0.36
	Tandem	0.53

Table 3

Preseason and postseason force plate metric summary, mean (SD). Averages were computed between subjects for each time point (preseason and preseason) and condition (eyes open and eyes closed).

	Preseason		Postseason	
	Eyes Open	Eyes Open	Eyes Open	Eyes Open
<i>AP Sway (cm)</i>	0.47 (0.18)	0.54 (0.23)	0.43 (0.18)	0.55 (0.23)
<i>ML Sway (cm)</i>	0.33 (0.18)	0.42 (0.20)	0.33 (0.27)	0.36 (0.18)
<i>Path Length (cm)</i>	17.03 (8.50)	23.61 (11.03)	15.54 (5.35)	21.83 (8.72)
<i>Max Path Velocity (cm/s)</i>	4.36 (1.12)	4.73 (1.08)	4.21 (0.88)	4.55 (1.23)
<i>95% Ellipse Area (cm²)</i>	3.06 (2.85)	4.31 (3.16)	2.56 (2.86)	3.78 (3.16)
<i>Renyi Entropy</i>	3.44 (0.27)	3.54 (0.33)	3.53 (0.24)	3.49 (0.35)
<i>Shannon Entropy</i>	2.52 (0.15)	2.52 (0.14)	2.48 (0.20)	2.51 (0.18)
<i>AP Entropy</i>	0.34 (0.11)	0.45 (0.10)	0.33 (0.09)	0.42 (0.11)
<i>ML Entropy</i>	0.32 (0.10)	0.37 (0.11)	0.31 (0.08)	0.36 (0.11)