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Balance Regularity Among Former High School Football Players With or Without a History of Concussion

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Context: Subclinical postural-control changes may persist beyond the point when athletes are considered clinically recovered postconcussion.

Objective: To compare postural-control performance between former high school football players with or without a history of concussion using linear and nonlinear metrics.

Design: Case-control study.

Setting: Clinical research laboratory.

Patients or Other Participants: A total of 11 former high school football players (age range, 45–60 years) with 2 or more concussions and 11 age- and height-matched former high school football players without a history of concussion. No participant had college or professional football experience.

Main Outcome Measure(s): Participants completed the Sensory Organization Test. We compared postural control (linear: equilibrium scores; nonlinear: sample and multiscale entropy) between groups using a 2 × 3 analysis of variance across conditions 4 to 6 (4: eyes open, sway-referenced platform; 5: eyes closed, sway-referenced platform; 6: eyes open, sway-referenced surround and platform).

Results: We observed a group-by-condition interaction effect for medial-lateral sample entropy ($F_{2,40} = 3.26$, $P = .049$, $\eta_p^2 = 0.140$). Participants with a history of concussion presented with more regular medial-lateral sample entropy values (0.90 ± 0.41) for condition 5 than participants without a history of concussion (1.30 ± 0.35; mean difference = –0.40; 95% confidence interval [CI] = –0.74, –0.06; $t_{20} = -2.48$, $P = .02$), but conditions 4 (mean difference = –0.11; 95% CI: –0.37, 0.15; $t_{20} = -0.86$, $P = .40$) and 6 (mean difference = –0.25; 95% CI: –0.55, 0.06; $t_{20} = -1.66$, $P = .11$) did not differ between groups.

Conclusions: Postconcussion deficits, detected using nonlinear metrics, may persist long after injury resolution. Subclinical concussion deficits may persist for years beyond clinical concussion recovery.

Key Words: mild traumatic brain injuries, postural stability, retired athletes

Key Points

- Former high school football players with a history of concussion presented with more regular balance performance when balancing in double-legged stance with eyes closed on a sway-referenced platform.
- Subclinical concussion deficits may persist well beyond clinical concussion recovery, but more investigation is needed to follow individuals prospectively postconcussion.
- Applying nonlinear metrics to a clinical setting presents challenges because of the computational rigor and difficulty interpreting a value's meaning, and research is needed to identify adaptations to these methods to make the metrics clinically feasible.

American football has come under great scrutiny[1] due to research[2–4] revealing a possible link between concussion history or head-trauma exposure and later-life impairments, such as an elevated risk of clinically diagnosed depression, mild cognitive impairment, earlier onset of Alzheimer disease, and the heavily debated chronic traumatic encephalopathy. Authors of this growing body of literature have indicated that athletes who sustain a concussion may have subclinical changes (ie, not severe enough to present in observable symptoms) occurring in the brain that are not evident until later in life.

A multidisciplinary postconcussion evaluation typically includes a clinical examination, symptom assessment, neuropsychological testing, and balance assessment.[5] Using this evaluation and treatment paradigm, concussion recovery has been reported to take approximately 7 to 10 days among collegiate student-athletes.[2,6] Balance impairments have been observed to resolve within 3 to 5 days postconcussion, which is more quickly than neuropsychological performance and concussion symptoms resolve.[2,6] Traditionally, balance has been evaluated with clinical measures that use linear measurements of sway, under the assumption that increased sway indicates poorer balance.

Whereas the medical community has accepted the expected 7- to 10-day recovery window as the average duration of concussion recovery, researchers[7–11] using nonlinear metrics of balance have indicated that lingering subclinical changes may persist beyond this time frame. *Dynamic systems theory* is an area of applied mathematics used to describe the behavior of a dynamic system over a time series.[12] *Approximate entropy* (ApEn) is a nonlinear measure representing the regularity of a system, which is expressed as the likelihood that a sequential order of data will reappear within the time series. Higher entropy values indicate greater irregularity and less regularity. Cavanaugh et al[7,8] reported that athletes with an acute concussion presented with more regular (ie, lower ApEn) center-of-pressure (COP) alignment than control participants. Differences in regularity persisted beyond the point when the participants were determined to be clinically recovered and ready to return to sport participation.[7,8] Lower ApEn values may indicate that athletes with a concussion adopt a more conservative, less complex, and more regular balance strategy.

Conservative postconcussion balance strategies have been observed. More regular COP alignment values have also been reported among individuals with a history of concussion at an average of 1.5 to 3.5 years postconcussion.[10,13] During gait, individuals with a history of concussion adopt a more conservative strategy by spending more time in a double-legged stance, spending less time in a single-legged stance, and using a slower gait velocity.[9] Collectively, these authors have demonstrated that subtle indicators of continued brain recovery may persist beyond the recovery window. Nonlinear metrics of balance have been identified as a "fertile area for future study to further the understanding of postural-control impairments"[14(p1)] postconcussion. However, little research exists regarding long-term balance performance postconcussion. Therefore, the purpose of our study was to compare postural-control performance between former high school football players with or without a history of concussion using linear and nonlinear metrics. We hypothesized that former high school football players with a history of multiple concussions would present with a more regular COP sway pattern than players without a history of concussion but that no differences would exist in linear metrics.

METHODS

Participants

This cross-sectional study was conducted as part of a larger protocol that included neuropsychological assessment and neuroimaging.[15,16] Former high school football players were recruited through advertisements and news articles or contacted using public records and alumni LISTSERV e-mail lists (L-Soft International, Inc, Bethesda, MD). Participants were included if they self-reported right-hand dominance (necessary for functional brain imaging due to lateralization of language and memory functioning), were male, and were aged 40 to 65 years. We selected this age range to limit the frequency of people who might be experiencing age-related deterioration of cognitive and motor control yet were well beyond the original concussion period. Volunteers were excluded if they were unable to undergo magnetic resonance imaging or if they reported being illiterate; being left-hand dominant; learned English as a second language; had a history of alcohol or drug abuse or dependency within the 5 years before the study, substantial neurologic disorder, a developmental learning disorder, bipolar disorder, or schizophrenia; or were currently using any psychotropic medications. Participants were provided with a small monetary compensation for their time.

Former high school football players were categorized into the concussion-history group (n = 11) if they reported sustaining 2 or more concussions in the context of their high school football experiences and no concussions outside this period or sport. As such, their most recent concussion was at least 15 years before examination. Participants with 1 concussion were not included in the study. Age-matched (±4 years) former high school football players with no concussion history (n = 11) were selected for the control group. Concussions were identified using a 2-step process that included a self-report questionnaire followed by a semistructured interview. Participants completed a self-report questionnaire regarding concussion history in which a mild traumatic brain injury was diagnosed when at least 1 of the following criteria was met after an injury involving the head: loss of consciousness for less than 30 minutes, retrograde amnesia, alteration in mental state (eg, feeling dazed, disoriented, or confused), or focal neurologic deficit(s) that might or might not have been transient.[17] Next, we administered the Acute Concussion Evaluation[18] to confirm their group assignment. It assesses the following injury characteristics: details of the blow to the head, a 22-symptom checklist for symptoms at the time of injury, 5 signs associated with mild traumatic brain injury, and risk factors that might predict a prolonged recovery. The Acute Concussion Evaluation has moderate to high internal consistency (α coefficient = 0.82) and adequate content, predictive, and convergent validity when compared with other concussion assessments.[18] The minimum number of years between recruitment and the most recent concussion was 22 years. Demographic information for both groups is presented in the Table. All participants provided written informed consent, and the study was approved by the Institutional Review Board at the University of Georgia.

Data Collection

Participants completed a demographic form, concussion-history interview, and a balance assessment (Sensory Organization Test [SOT]). Neuropsychological testing and magnetic resonance imaging were also completed as part of a larger cross-sectional study.[15,16]

Symptom Assessment. A 22-item concussion-symptom checklist was administered to index current, if any, postconcussive symptoms for both groups. Participants ranked both the duration and severity of each symptom in the 24 hours before the study using Likert scales (range, 0–6; Table). Duration was ranked as 0 (*not experiencing*), 1 or 2 (*briefly*), 3 or 4 (*sometimes*), or 5 or 6 (*always*), and severity was ranked as 0 (*not experiencing*), 1 or 2 (*mild*), 3 or 4 (*moderate*), or 5 or 6 (*severe*).[19]

Postural-Control Assessment. Participants completed postural-control assessment using the SOT on the SMART Balance Master (NeuroCom International, Clackamas, OR). We instructed them to stand shoeless on two 9- × 18-in (22.86- × 45.72-cm) force plates connected by a pin joint with their upper extremities relaxed at their sides, looking straight ahead, and as still as possible. Foot placement was standardized according to the manufacturer's protocol; their feet were placed approximately shoulder-width apart, and the medial malleoli were aligned with markings on the force plate that corresponded to their height. Both the

Table. Demographic, Symptom-Assessment, and Concussion-History Information for the Concussion-History and No–Concussion-History Groups

Demographic Variable	Group		P Value
	Concussion History (n = 11)	No Concussion History (n = 11)	
Age, y (mean ± SD)	50.5 ± 7.5	50.8 ± 6.6	.91
Height, cm (mean ± SD)	182.2 ± 6.9	182.1 ± 7.1	.25
Mass, kg (mean ± SD	88.2 ± 11.2	95.2 ± 13.5	.20
Education, y (mean ± SD)	14.9 ± 2.6	15.2 ± 2.1	.79
Premorbid intelligence quotient (mean ± SD)	109.7 ± 7.3	108.7 ± 15.6	.85
Assessment of current symptoms (mean ± SD)			
Total No. of symptoms	5.8 ± 4.7	4.5 ± 2.8	.45
Total symptom severity score	16.1 ± 15.4	9.1 ± 5.8	.17
Total symptom duration score	19.8 ± 19.8	11.5 ± 7.8	.21
Concussion history			
Total No. of concussions (mean ± SD)	5.6 ± 5.2	0.0 ± 0.0	.002[a]
Concussions with loss of consciousness (%)	27.3	NA	NA
Concussions receiving medical attention (%)	29.1	NA	NA
Concussions with memory lapse (%)	27.9	NA	NA

Abbreviation: NA, not applicable.

[a] Difference ($P < .05$).

support surface and visual surround rotated in the anterior-posterior plane referenced to the athlete's sway and sway velocity. Center-of-pressure data were sampled at 100 Hz. The SOT consists of 6 sensory conditions repeated 3 times for a total of eighteen 20-second trials. The 6 sensory conditions were eyes open with a stationary support surface (condition 1), eyes closed with a stationary support surface (condition 2), sway-referenced visual input with a stationary support surface (condition 3), eyes open with a sway-referenced support surface (condition 4), eyes closed with a sway-referenced support surface (condition 5), and eyes open with a sway-referenced visual and support surface (condition 6). The SOT has been described in detail.[20,21]

Center-of-Pressure Data Analysis

Researchers were blinded to group assignment throughout data reduction.

Linear Metrics. To represent the clinical biomechanical outcome measure of postural-control performance, we generated equilibrium scores for each trial for each SOT condition based on the algorithm developed for the SMART Balance Master system.[20] The algorithm uses the peak-to-peak amplitude of COP displacement to estimate the amount of postural sway in the sagittal plane. The equilibrium score is expressed as the angular distance (percentage) between the amount of estimated anterior-posterior postural sway and the theoretic limit of stability (approximately 12.5°). A higher equilibrium score indicates better postural control.

Sample Entropy. Center-of-pressure data along the anteroposterior (AP) and mediolateral (ML) axes were exported for each trial. Sample entropy (SampEn), a refinement of ApEn,[22] was applied to determine how likely a particular sequence in the time series was to reappear and was calculated as follows:

$$\mathrm{SampEn}(m, r, N) = -\ln \frac{C^{m+1}(r)}{C^{m}(r)}, \tag{1}$$

where m is the length of the repetition vector that will be compared, r is the similarity criterion, N is the number of COP data points, ln is the natural log, and $C^m(r)$ is the correlation sum. In this study, we selected $m = 2$ and $r = 0.2$ to calculate SampEn because, under a data-length N ranging from 100 to 5000 when $m = 2$ and r is a number between 0.1 and 0.25, the SampEn shows highly reasonable statistical validity.[23] The SampEn provides a lowest value of zero; however, no limit number exists for the upper value. A sine wave representing high regularity would have a SampEn value approaching zero, whereas white noise representing a random, irregular signal would have a SampEn value approaching infinity. Therefore, lower entropy values indicate a more regular balance performance.

Multiscale Entropy. Multiscale entropy (MSE) was also conducted for a second nonlinear metric. Traditional nonlinear measures, such as ApEn and SampEn, have been widely used to investigate the regularity of human physiologic time-series data. However, Gao et al[24] reported that those metrics have the disadvantage of estimating the regularity on a single time scale, although the physiologic time series are strongly dependent on multiple time scales (eg, slow or fast time scale). Therefore, we introduced MSE, taking into consideration the multiple time scales for a measure of regularity.[25]

Several steps were required to implement MSE. First, a coarse-grained time series that is a successive smoothing time series was built from the original COP time series. It was created by averaging a continuously increasing number of data points called *time-scale factor* (τ) in nonoverlapping windows. In our study, 20 time-scale factors (range, 1–20) produced 20 coarse-grained time series of different lengths (N/τ). Second, SampEn was calculated for each time series using Equation 1.

Third, an MSE curve showing the SampEn as a function of time-scale factor (i) was created. It provided information about the regularity of the COP on multiple time scales. Fourth, an index of the regularity representing a nonlinear metric of MSE was investigated by calculating the area under the MSE curve[26] as follows:

$$\text{MSE area} = \sum_{i=1}^{20} \text{SampEn(i)} \quad (2)$$

A higher value indicates less regularity, and a lower value indicates greater regularity. Equilibrium scores, SampEn, and MSE values were averaged across the 3 trials for each condition.

Statistical Analysis

Separate 2 (group) × 3 (conditions 4–6) mixed-model analyses of variance were used to compare AP and ML equilibrium scores, SampEn, and MSE values about the AP and ML axes between groups across SOT conditions 4 to 6 ($\alpha = .05$). We analyzed only conditions 4 to 6 because these use a sway-referenced platform, which we hypothesized to be the most likely to reveal impairments. Conditions 1 and 2 are used to calculate clinical ratios that were not of interest in this study. We calculated the η_p^2 to determine effect sizes, which were interpreted as *small* (0.01), *medium* (0.06), or *large* (0.14). Post hoc testing was conducted using independent-samples *t* tests when we observed differences. Statistical analyses were conducted using SPSS (version 23.0; IBM Corp, Armonk, NY). The α level was set a priori at .05.

RESULTS

Groups did not differ on any demographic variables other than concussion history (Table). We did not observe group-by-condition interaction effects for equilibrium scores ($F_{2,40} = 0.82$, $P = .45$, $\eta_p^2 = 0.039$), AP SampEn ($F_{2,40} = 0.55$, $P = .58$, $\eta_p^2 = 0.027$), AP MSE ($F_{2,40} = 1.28$, $P = .29$, $\eta_p^2 = 0.060$), or ML MSE ($F_{2,40} = 0.06$, $P = .94$, $\eta_p^2 = 0.003$) across SOT conditions. A group-by-condition interaction effect was present for ML SampEn ($F_{2,40} = 3.26$, $P = .049$, $\eta_p^2 = 0.140$). Participants with a history of concussion presented with lower ML SampEn values (0.90 ± 0.41) on condition 5 than participants without a history of concussion (1.30 ± 0.35; mean difference = –0.40; 95% confidence interval [CI] = –0.74, –0.06; $t_{20} = -2.48$, $P = .02$), but conditions 4 (mean difference = –0.11; 95% CI = –0.37, 0.15; $t_{20} = -0.86$, $P = .40$) and 6 (mean difference = –0.25; 95% CI = –0.55, 0.06; $t_{20} = -1.66$, $P = .11$) did not differ between groups (Figure).

We did not demonstrate main effects for group (η_p^2 range, 0.009–0.157). A main effect for condition was noted for equilibrium scores ($F_{2,40} = 69.05$, $P < .001$, $\eta_p^2 = 0.775$), AP SampEn ($F_{2,40} = 164.49$, $P < .001$, $\eta_p^2 = 0.892$), ML SampEn ($F_{2,40} = 29.88$, $P < .001$, $\eta_p^2 = 0.599$), and AP MSE ($F_{2,40} = 8.41$, $P = .001$, $\eta_p^2 = 0.296$) but not for ML MSE ($F_{2,40} = 2.67$, $P = .08$, $\eta_p^2 = 0.117$). Condition 4 resulted in greater equilibrium scores than conditions 5 (mean difference = 21.23; $P < .001$) and 6 (mean difference = 24.74; $P < .001$), but conditions 5 and 6 did not differ (mean difference = 3.52; $P = .17$). We observed lower ML SampEn for condition 4 than for conditions 5 (mean difference = –0.42; $P < .001$) and 6 (mean difference = –0.34; $P < .001$), but conditions 5 and 6 did not differ (mean difference = –0.09; $P = .19$). Condition 4 resulted in lower AP SampEn than conditions 5 (mean difference = –0.81; $P < .001$) and 6 (mean difference = –0.86; $P < .001$), but conditions 5 and 6 did not differ (mean difference = –0.06; $P = .36$; Figure).

DISCUSSION

To our knowledge, we are the first to examine nonlinear metrics of balance among former high school football players with or without a history of multiple concussions. As hypothesized, former high school football players with or without a history of concussion presented with similar balance performance when analyzed using traditional linear metrics. We found, however, that when analyzed using SampEn, participants with a history of concussion presented with more regular balance performance in the ML direction while balancing double legged with eyes closed on a sway-referenced support surface. The results of our study complement those of researchers who have reported that individuals with acute concussion[7,8] and collegiate athletes with a history of concussion[10,13] present with balance impairments that persist beyond the typical 7- to 10-day recovery window.[2,6]

Our observation of a more regular COP pattern among the group with a history of concussion is compatible with the loss-of-complexity hypothesis of aging and disease.[27] When applied to balance, the theory implies that the complex integration of afferent and efferent visual, vestibular, and somatosensory processing loops is impaired by concussion, which manifests as less intricate postural control over a time series. Condition 5 of the SOT is often the most challenging because the participants lack a visual stimulus (eyes closed) and have inaccurate somatosensory stimulus (sway-referenced support surface), causing them to rely solely on the vestibular system. All other conditions, except condition 5, provide stimulation of at least 2 of the 3 sensory systems. We observed an interaction effect for condition 5 only; however, descriptive analysis of group-by-condition means revealed that the group with a concussion history consistently presented with a pattern of lower SampEn values than the group with no concussion history across all conditions. We found small effect sizes for some interaction effects, which may explain why these differences were not evident across all conditions.

Our results are similar to those of De Beaumont et al[13] and Sosnoff et al,[10] who examined postural regularity using ApEn among college-aged athletes with or without a history of concussion. De Beaumont et al[13] demonstrated that football players with a history of concussion exhibited more COP regularity in the AP direction. Sosnoff et al[10] noted more COP regularity in conditions 5 and 6 among athletes with a history of concussion in the ML direction but less regularity in the AP direction. As a whole, our results combined with previous results suggest that individuals with a history of concussion applied different postural strategies during the SOT than those without a history of concussion. Our study adds to the body of literature by further elucidating that balance differences are also detectable in midlife. It is possible that subclinical concussion deficits persist well beyond clinical recovery from concussion, as we examined former high school football players in middle age, but more research is needed to follow such individuals prospectively after their injuries. Whereas differences in balance regularity have been found

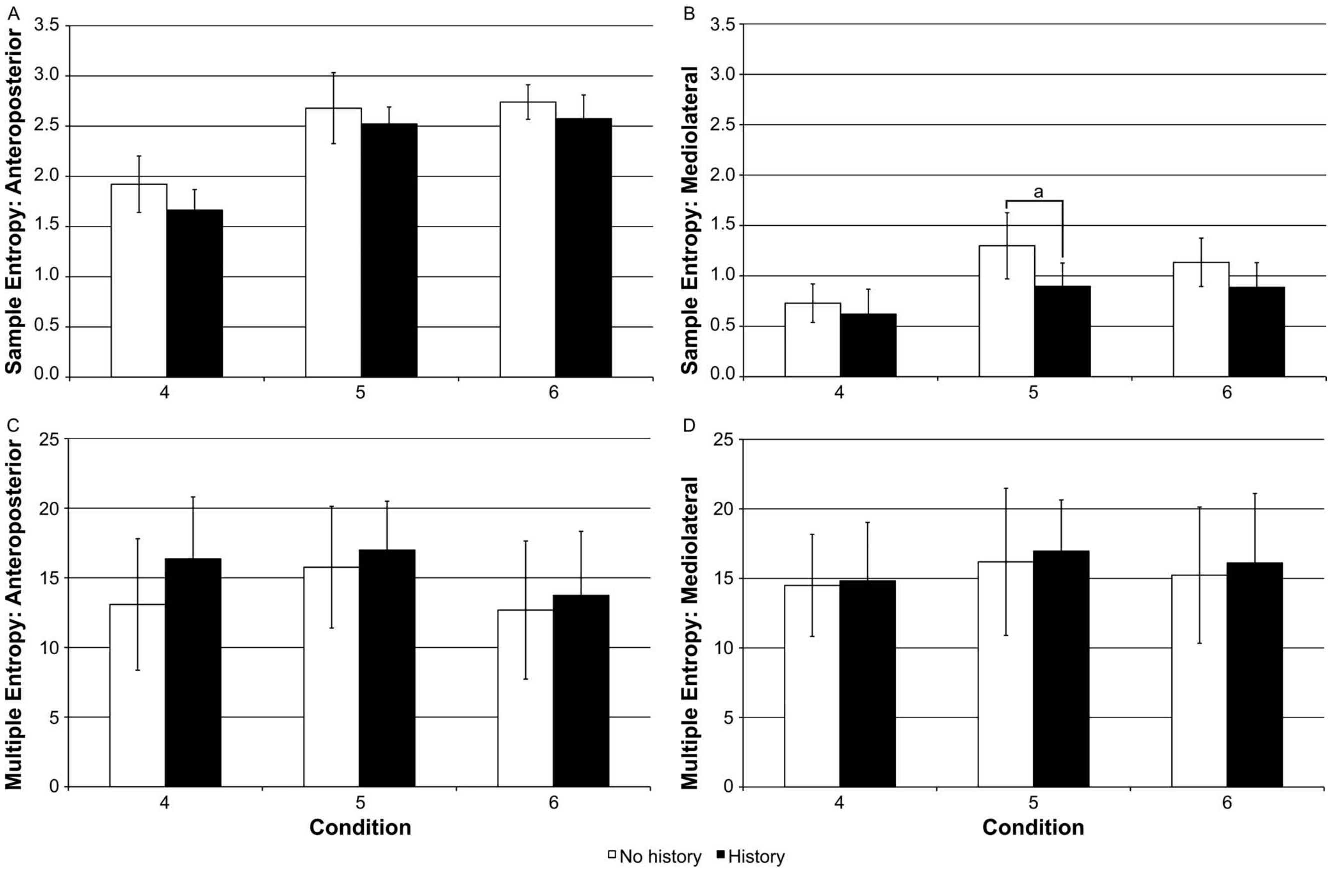

Figure. Sample and multiscale entropy across Sensory Organization Test conditions for the concussion-history and no–concussion-history groups. A, Anteroposterior sample entropy. B, Mediolateral sample entropy in the medial-lateral direction. C, Anteroposterior multiscale entropy. D, Mediolateral multiscale entropy. [a] Difference between groups ($P = .02$).

in both the AP and ML directions, suppressed postural control in the ML direction, as observed in our study, may have more implications for an increased risk of falls.[28] However, more investigation is needed to determine whether sustaining a concussion during adolescence leads to subclinical concussion deficits that persist beyond clinical recovery from concussion.

Similarly to previous studies,[7,8,10,13] our linear metrics for overall COP displacement did not differ between groups. The lack of group differences in equilibrium scores indicated that the traditional metrics from the SOT may not be sensitive to balance deficits beyond the acute stage of concussion recovery.[14] Clinicians should recognize these limitations and understand that clinically meaningful changes in postural control from the persistent effects of concussion may be more evident with more sensitive measures of both static and dynamic balance. Entropy values may add to measurement sensitivity because they mathematically account for the sequential order of successive data points. Applying nonlinear metrics to a clinical setting presents challenges due to the computational rigor and difficulty of interpreting a value's meaning. More work is needed to identify adaptations to this method that would make these metrics clinically feasible.

Whereas the 2 groups had the same amount of COP displacement, the group with a history of concussion used a more regular approach during condition 5. Individuals with a history of concussion may learn compensatory balance strategies that mask balance impairments when analyzed using linear metrics, but these difficulties become evident when using nonlinear metrics. If clinicians were to look at equilibrium scores only, they would conclude that having a history of concussion does not influence balance performance among former high school football players. Differences in balance regularity may indicate compensations that place individuals with a previous concussion at risk. Although not examined in this study, residual balance deficits that persist postconcussion may partially explain why athletes with a history of concussion have an increased risk of subsequent musculoskeletal injury.[29–31] Further research is needed to determine how concussion-related balance impairments manifest in middle to late life.

As is true with all research involving concussion history, having to rely on a self-reported concussion history to recall injuries that occurred years before testing is not optimal. We used a comprehensive interview process to best address concussion-history recall, but we recognize that recall may not be completely accurate. By separating participants into history and no-history groups, we likely accounted for recall inaccuracies. Our study did not include a noncontact-athlete or nonathlete control group. Further study is needed to determine whether concussions or nonconcussive head impacts from football influence late-life postural control performance.

The SOT examines postural control predominantly in the sagittal plane. We did not control for a history of lower extremity injury; however, no major restrictions were noted. Finally, our results were cross-sectional and only correlational. Investigators should prospectively study subclinical balance deficits beyond the point of clinical recovery.

CONCLUSIONS

Concussion recovery has been proposed to take approximately 7 to 10 days among collegiate student-athletes.[2,6] Our study contributes to the growing body of literature showing that postconcussion deficits persist long after injury resolution. Subclinical concussion deficits may persist well beyond clinical recovery from concussion into midlife to late life.

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REFERENCES

1. Greenhow A, East J. Custodians of the game: ethical considerations for football governing bodies in regulating concussion management. *Neuroethics*. 2015;8(1):65–82.
2. Guskiewicz KM. Postural stability assessment following concussion: one piece of the puzzle. *Clin J Sport Med*. 2001;11(3):182–189.
3. Guskiewicz KM, Marshall SW, Bailes J, et al. Association between recurrent concussion and late-life cognitive impairment in retired professional football players. *Neurosurgery*. 2005;57(4):719–726.
4. McKee AC, Stein TD, Nowinski CJ, et al. The spectrum of disease in chronic traumatic encephalopathy. *Brain*. 2013;136(pt 1):43–64.
5. McCrory P, Meeuwisse WH, Aubry M, et al. Consensus statement on concussion in sport: the 4th International Conference on Concussion in Sport, Zurich, November 2012. *J Athl Train*. 2013;48(4):554–575.
6. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *JAMA*. 2003;290(19):2556–2563.
7. 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. *Br J Sports Med*. 2005;39(11):805–811.
8. Cavanaugh JT, Guskiewicz KM, Giuliani C, Marshall S, Mercer V, Stergiou N. Recovery of postural control after cerebral concussion: new insights using approximate entropy. *J Athl Train*. 2006;41(3): 305–313.
9. Martini DN, Sabin MJ, DePesa SA, et al. The chronic effects of concussion on gait. *Arch Phys Med Rehabil*. 2011;92(4):585–589.
10. Sosnoff JJ, Broglio SP, Shin S, Ferrara MS. Previous mild traumatic brain injury and postural-control dynamics. *J Athl Train*. 2011;46(1): 85–91.
11. Slobounov S, Cao C, Sebastianelli W, Slobounov E, Newell K. Residual deficits from concussion as revealed by virtual time-to-contact measures of postural stability. *Clin Neurophysiol*. 2008; 119(2):281–289.
12. Harbourne RT, Stergiou N. Movement variability and the use of nonlinear tools: principles to guide physical therapist practice. *Phys Ther*. 2009;89(3):267–285.
13. De Beaumont L, Mongeon D, Tremblay S, et al. Persistent motor system abnormalities in formerly concussed athletes. *J Athl Train*. 2011;46(3):234–240.
14. Buckley TA, Oldham JR, Caccese JB. Postural control deficits identify lingering post-concussion neurological deficits. *J Sport Health Sci*. 2016;5(1):61–69.
15. Terry DP, Adams TE, Ferrara MS, Miller LS. FMRI hypoactivation during verbal learning and memory in former high school football players with multiple concussions. *Arch Clin Neuropsychol*. 2015; 30(4):341–355.
16. Terry DP, Faraco CC, Smith D, Diddams MJ, Puente AN, Miller LS. Lack of long-term fMRI differences after multiple sports-related concussions. *Brain Inj*. 2012;26(13–14):1684–1696.
17. Mild Traumatic Brain Injury Committee of the Head Injury Interdisciplinary Special Interest Group of the American Congress of Rehabilitation Medicine. Definition of mild traumatic brain injury. *J Head Trauma Rehabil*. 1993;8(3):86–87.
18. Gioia GA, Collins M, Isquith PK. Improving identification and diagnosis of mild traumatic brain injury with evidence: psychometric support for the acute concussion evaluation. *J Head Trauma Rehabil*. 2008;23(4):230–242.
19. Broglio SP, Macciocchi SN, Ferrara MS. Neurocognitive performance of concussed athletes when symptom free. *J Athl Train*. 2007; 42(4):504–508.
20. *Equitest System Data Interpretation Manual*. Clackamas, OR: Neurocom International Inc; 1991.
21. Nashner LM. Computerized dynamic posturography. In: Jacobson GP, Shepard NT, eds. *Balance Function Assessment and Management*. 2nd ed. San Diego, CA: Plural Publishing; 2016:451–478.
22. Yentes JM, Hunt N, Schmid KK, Kaipust JP, McGrath D, Stergiou N. The appropriate use of approximate entropy and sample entropy with short data sets. *Ann Biomed Eng*. 2013;41(2):349–365.
23. Groome LJ, Mooney DM, Holland SB, Smith LA, Atterbury JL, Loizou PC. Human fetuses have nonlinear cardiac dynamics. *J Appl Physiol*. 1999;87(2):530–537.
24. Gao J, Hu J, Tung W. Entropy measures for biological signal analyses. *Nonlinear Dyn*. 2012;68(3):431–444.
25. Costa M, Peng CK, Goldberger AL, Hausdorff JM. Multiscale entropy analysis of human gait dynamics. *Physica A*. 2003;330:53–60.
26. Costa M, Priplata AA, Lipsitz LA, et al. Noise and poise: enhancement of postural complexity in the elderly with a stochastic-resonance-based therapy. *Europhys Lett*. 2007;77(6): 68008.
27. Lipsitz LA, Goldberger AL. Loss of "complexity" and aging: potential applications of fractals and chaos theory to senescence. *JAMA*. 1992;267(13):1806–1809.
28. Piirtola M, Era P. Force platform measurements as predictors of falls among older people: a review. *Gerontology*. 2006;52(1):1–16.
29. Brooks MA, Peterson K, Biese K, Sanfilipo J, Heiderscheit BC, Bell DR. Concussion increases odds of sustaining a lower extremity musculoskeletal injury after return to play among collegiate athletes. *Am J Sports Med*. 2016;44(3):742–747.
30. Pietrosimone B, Golightly YM, Mihalik JP, Guskiewicz KM. Concussion frequency associates with musculoskeletal injury in retired NFL players. *Med Sci Sports Exerc*. 2015;47(11):2366–2372.
31. Lynall RC, Mauntel TC, Padua DA, Mihalik JP. Acute lower extremity injury rates increase after concussion in college athletes. *Med Sci Sports Exerc*. 2015;47(12):2487–2492.

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