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Previous Mild Traumatic Brain Injury and Postural-Control Dynamics

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Context: Postural control and cognitive function are adversely affected by acute mild traumatic brain injury (mTBI). Whether postural-control deficits persist beyond the acute stage in individuals with a history of mTBI is unclear.

Objective: To determine if postural-control deficits persist in individuals with a history of mTBI.

Design: Retrospective cross-sectional study.

Setting: University research laboratory.

Patients or Other Participants: As part of an ongoing investigation examining cognitive and motor deficits associated with mTBI, 224 individuals participated in the study. Of these, 62 participants self-reported at least 1 previous physician-diagnosed mTBI.

Intervention(s): Postural control was assessed using the NeuroCom Sensory Organization Test (SOT) postural-assessment battery.

Main Outcome Measure(s): The SOT postural assessment yields 4 indices of postural control: a composite balance score, a visual ratio score, a somatosensory score, and a vestibular score. Postural dynamics were also examined by calculating approximate entropy of center-of-pressure excursions in the anteroposterior and mediolateral axis for each test condition.

Results: Minimal differences in the SOT indices were noted among individuals with and without a history of previous mTBI ($P > .05$). In the group with a history of mTBI, anteroposterior postural irregularity decreased as postural difficulty increased. In contrast, the group without a history of mTBI displayed increased postural irregularity in the mediolateral direction.

Conclusions: Individuals with a history of mTBI exhibited altered postural dynamics compared with individuals without a history of mTBI. These findings support the notion that changes in cerebral functioning that affect postural control may persist long after acute injury resolution.

Key Words: concussions, balance, complexity analysis, long-term effects, nonlinear dynamics

Key Points

- Traditionally, mild traumatic brain injury has been thought to result in short-lived impairment of postural control and neurocognitive functioning.
- However, on the Sensory Organization Test, as the task difficulty increased, previously concussed individuals displayed decreased anteroposterior postural irregularity, whereas nonconcussed individuals displayed increased mediolateral postural irregularity.
- After concussion, subtle changes in cerebral function may persist long after the acute injury resolves.

Traumatic brain injury (TBI) results from a direct or indirect blow to the head that results in neuropathologic changes. In the United States, TBI represents a major medical concern that costs nearly $60 billion in direct and indirect expenses annually.[1] Most of these injuries are classified as mild TBI (mTBI), with an estimated 1.6 to 3.8 million injuries occurring in the United States annually as a result of sport participation.[2] This estimate likely represents underreporting: in one study,[3] more than 50% of high school athletes failed to report their injuries to medical personnel.

Clinical observation of concussed individuals reveals impaired postural control in the days immediately after injury. The effects of impaired postural control have been shown to be large,[4] with impaired sensory integration postulated as the source of imbalance. Although the details have been outlined previously (see Guskiewicz[5] for review), they warrant a brief discussion. Postural control is maintained through the combined afferent information generated by the somatosensory, visual, and vestibular systems. In healthy individuals, these systems work together to provide environmental information that modulates the motor patterns to accommodate current conditions. In concussed individuals, however, researchers[6,7] using the Sensory Organization Test (SOT) reported postinjury postural-control decrements in the form of suppressed composite-score performance. A further examination of the postural-control mechanism indicated impaired visual and vestibular ratio scores. The authors considered the change in overall balance to be driven by suppressed visual and vestibular system functioning or the inefficient integration of vestibular information, particularly when the eyes were closed. Yet the balance deficits quantified by the SOT appeared to resolve by approximately 3 days postinjury.[6,8]

Traditionally, postural control is indexed by distributional statistics quantifying the amount of sway. It is assumed that the increased amounts of sway correspond with decreased postural control. A limitation of these measures is that they do not characterize the time-dependent dynamics of postural control. Nonlinear dynamical measures such as approximate entropy (ApEn) have been successfully used to characterize the dynamics of postural control.[9] The ApEn is based on how likely a given pattern is to reappear within the time series. Specific to postural control, a person swaying in a very predictable manner would have a low ApEn value, whereas a person swaying in an irregular manner would have a higher ApEn value. Traditionally, a lower ApEn value indicates decreased function. Furthermore, it has been argued[10] that these measures are more sensitive to injury than are traditional postural-control measures. Specific to concussion, Cavanaugh et al[9] demonstrated that compared with a healthy control group, athletes who had suffered a concussion but who displayed normal postural stability on the SOT had subtle alterations in their postural dynamics, quantified by ApEn. The authors proposed that ApEn analysis of postural control is a worthwhile addition to concussion assessment, but whether changes in postural-sway variability persist beyond the acute stage of injury is unknown.

In addition to the adverse effects of mTBI on postural control, the negative effect of acute mTBI on cognitive function is well established. For example, McCrea et al[11] demonstrated that acute cognitive decrements resolved within 7 days of injury with no apparent long-term effects. However, in recent case studies[12,13] using brain-imaging technologies, mTBI has been associated with persistent changes in brain function. In addition, emerging evidence[14,15] among older adults has demonstrated significant correlations between multiple concussions and a higher prevalence of late-life cognitive dysfunction. Although further investigations pertaining to persistent decrements in cognitive function are needed, these findings tentatively indicate that cognitive dysfunction may persist after mTBI.

Presently, there is a dearth of investigations evaluating the persistence of postural-control deficits beyond the acute stages of mTBI. Therefore, the purpose of our retrospective investigation was to evaluate those with and without a history of mTBI for persistent alterations in postural control.

METHODS

As part of an ongoing investigation on the acute effects of sport mTBI, collegiate athletes at high risk for injury from 2002 to 2005 (eg, American football, soccer, and gymnastics athletes) completed a preseason baseline assessment for concussive injuries. The test battery included evaluations of concussion-related symptoms, neurocognitive functioning, and postural control. Also, a brief questionnaire about demographic information and previous concussions was completed. Similar to the procedures of Guskiewicz et al,[14] previous concussion was determined by the athlete's retrospective recall of the injury. Specifically, each individual was asked to indicate the number of times he or she had been diagnosed by a medical professional (ie, physician or athletic trainer) with mTBI. All participants indicated that they were free from illnesses or acute injuries (including acute mTBI) known to affect postural control, and all provided written informed consent before testing. All participants who reported a history of concussion were at least 6 months postinjury. All procedures were approved by the institutional review board.

We used the NeuroCom SOT (NeuroCom International, Inc, Clackamas, OR), described elsewhere in detail,[15] for postural-control assessment. Briefly, the test uses 6 different conditions in which the support surface or visual surround (or both) moves in conjunction with the participant's center of pressure (Figure 1). The 6 conditions comprise the following: (1) eyes open, stable support; (2) eyes closed, stable support; (3) sway-referenced vision, stable support; (4) eyes open, sway-referenced support; (5) eyes closed, sway-referenced support; and (6) eyes open, sway-referenced vision, and sway-referenced support. Sway referencing involves an anteroposterior rotation of the platform or visual surround (or both) that occurs as a response to the individual's shifts in center of pressure. This process renders information obtained from the ankle joints (sway-referenced support) or vision (sway-referenced vision) unreliable for balance control. The center-of-pressure movements occurring throughout the test are used to generate 4 scores associated with postural control: composite balance, somatosensory ratio, visual ratio, and vestibular ratio. The composite balance score is a weighted average calculated from the mean performance in conditions 1 and 2 and the average of all trials in conditions 3 through 6. The somatosensory ratio is calculated by dividing the average condition 2 performance by the average condition 1 performance. The visual ratio is calculated by dividing the average condition 4 performance by the average condition 1 performance and the vestibular ratio by dividing the average condition 5 performance by the average condition 1 performance.[16] Higher values of the composite balance score and 3 ratios indicate greater postural control. Each condition was administered 3 times in a randomized pattern, for 18 total trials, with scores generated for composite balance and the somatosensory, visual, and vestibular ratios. The SOT lasted approximately 15 minutes.

To gain further insight into how previous mTBI might affect postural control, the raw data were extracted for each trial to calculate the center of pressure (COP) along the anteroposterior (AP) and mediolateral (ML) axes. The COP may be considered a reflection of the system's neuromuscular response to the imbalances of the body's center of gravity.[17] It was calculated based on the procedures provided by the manufacturer.[18]

The ApEn is a nonlinear dynamic statistic that indexes the likelihood of fluctuations (ie, patterns) in a time series reappearing.[19] The calculation of ApEn is based on determining how likely a given pattern (ie, a particular sequence in the time series) is to reappear within the time series. To calculate ApEn, 2 factors must be specified: m is the length of the pattern, and r denotes how similar patterns must be in order to be considered a "match." Specifically, ApEn is a measure of the logarithmic likelihood that runs of length $m + 1$ observations will be close, given that runs of length m are close, the closeness between observations being defined as a percentage (r) of the SD of the time series of interest. We set m to 5 and r to 10% of the COP SD.[9] The calculation of ApEn yields a single value that quantifies the regularity of a time series. A

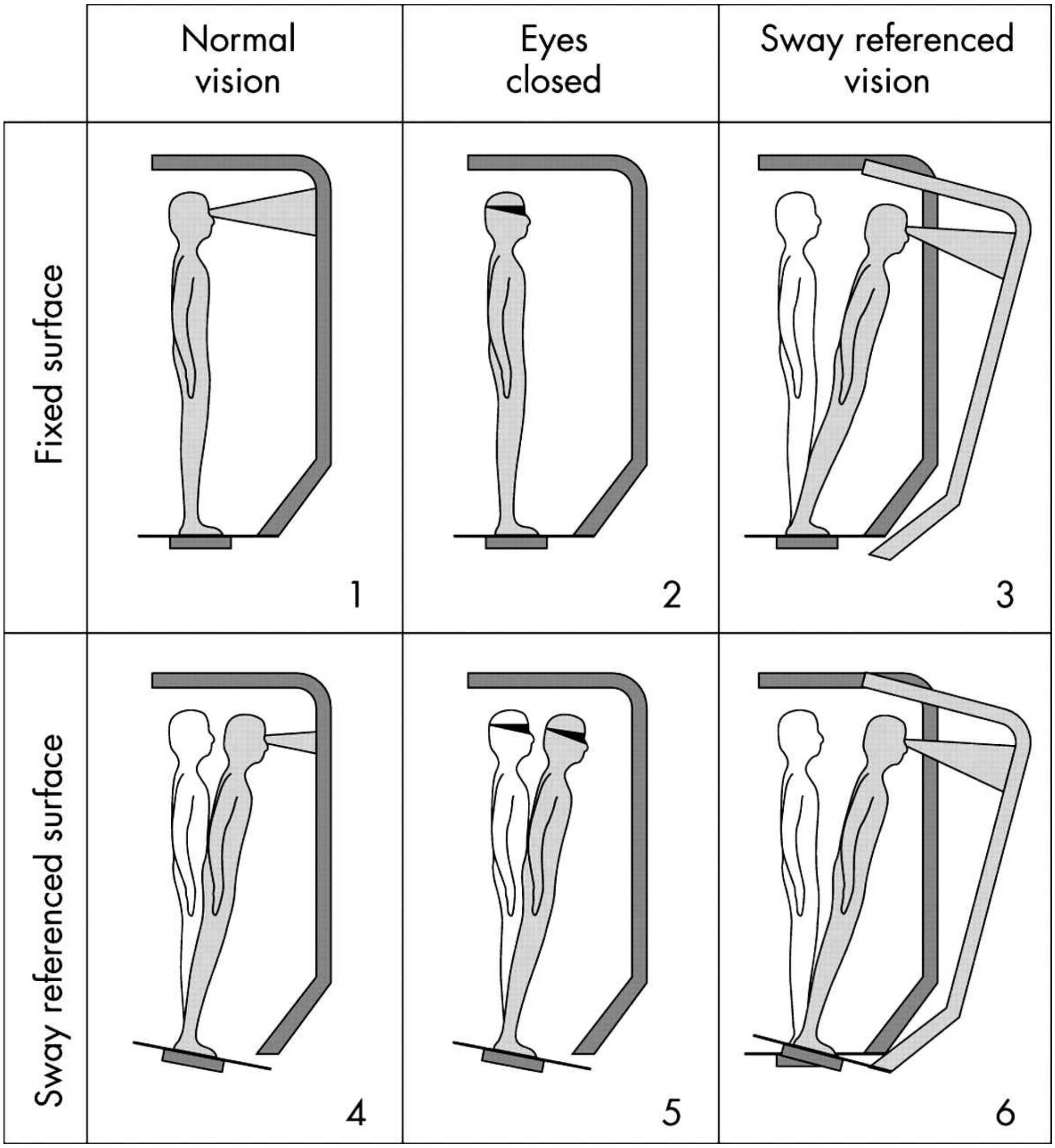

Figure 1. The 6 conditions of the NeuroCom Sensory Organization Test (SOT), used courtesy of NeuroCom International, Inc.

very regular signal, such as an ideal sine wave, which by definition has a large number of repeating patterns, would have an ApEn value approaching zero, whereas a random time series with minimal repeating patterns (eg, "white noise") would have a value close to 2. Thus, increases in ApEn reflect increases in the signal's time-domain complexity.[19] Traditionally, decrements in postural control are associated with lower values of ApEn.[10,19]

Data were grouped into participants with and without a history of medical professional (eg, physician or athletic trainer)–diagnosed concussion. Descriptive statistics were computed for the following dependent variables: balance score for SOT conditions 1 through 6, overall composite balance, somatosensory ratio, visual ratio, vestibular ratio, and ApEn of COP sway in AP and ML directions. To examine the effect of history of concussion on SOT performance, separate analyses of variance (ANOVAs) were conducted on each SOT variable (ie, composite balance and somatosensory, visual, and vestibular ratio), with concussion-history group as the between-subjects factor. To examine group differences in postural dynamics (eg, ApEn) along the AP and ML axes, separate 2-way, mixed-model, repeated-measures ANOVAs with condition (6) as the within-subjects factor and group (2) as the between-groups factor were calculated. When relevant, Bonferroni post hoc analyses were completed to determine the specific effects contributing to significant ANOVA results.[20]

Finally, in order to evaluate the relationship between time from injury and postural-control performance, Pearson correlation analyses between all postural-control measures and time since injury were conducted. All data analyses were conducted using SPSS (version 14.0; (SPSS Inc, Chicago, IL), and statistical significance was set at $P < .05$.

RESULTS

This retrospective analysis included 224 athletes (age = 20.04 $\pm$ 1.47 years: 152 males, 72 females) who received baseline assessments of postural control as part of an

Table. Sensory Organization Test Results (Mean ± SE)

Group	Composite Balance Score	Visual Ratio	Somatosensory Ratio	Vestibular Ratio
No history of concussion	91.26 ± 0.12	95.41 ± 0.18[a]	98.04 ± 0.08	89.86 ± 0.21
Previous concussion	91.58 ± 0.19	97.00 ± 0.18[a]	98.27 ± 0.14	90.67 ± 0.48

[a] Between-groups analysis: $P < .05$.

ongoing investigation of sport-related mTBI. A total of 162 athletes indicated that they had never sustained a concussion, whereas 62 had experienced at least 1 concussion (range = 1 to 4; 52 athletes sustained 1 concussion each, 6 athletes sustained 2 concussions each, 3 athletes sustained 3 concussions each, and 1 athlete sustained 4 concussions). Time since concussion ranged from 6.4 to 150.9 months (mean = 44.3 months, median = 40.3 months). Injury severity was not quantified because of the vast differences among the large number of published grading scales[21] and the bias inherent in recalling injury severity. Nor was loss of consciousness quantified, as it has been shown to not be a valid predictor of injury severity.[22]

Between-subjects ANOVAs for composite balance and for the somatosensory and vestibular ratio scores indicated no difference between groups (Table, all P values $> .05$). A group effect for visual-ratio score ($F_{1,223} = 26.66$, $P < .001$, $\eta^2 = .11$) was noted. The previously concussed group had a greater visual ratio score than did the nonconcussed group (97.00 versus 95.41).

Differences in AP postural-sway dynamics between the previously concussed and nonconcussed groups as a function of postural task are depicted in Figure 2. Statistical analysis revealed an effect of condition ($F_{2,223} = 58.42$, $P < .001$, $\eta^2 = .57$) and a group-by-condition interaction ($F_{2,223} = 7.58$, $P < .001$, $\eta^2 = .14$). Evaluation of the group-by-condition interaction indicated increased postural-sway irregularity in the previously concussed group (ie, increased ApEn values) as the postural-control task increased in difficulty (ie, progressed from condition 1 to condition 6). However, the nonconcussed group's postural-sway irregularity decreased as the task difficulty increased (ie, decreased ApEn values). Specifically, in conditions 1 through 4, the previously concussed group had lower ApEn values than the nonconcussed group but greater values in conditions 5 and 6 (all P values $< .05$).

The dynamics of ML postural sway throughout the SOT assessment are illustrated in Figure 3. Data analysis revealed a main effect for condition ($F_{5,223} = 49.86$, $P < .001$, $\eta^2 = .53$) and a group-by-condition interaction ($F_{5,223} = 96.53$, $P < .001$, $\eta^2 = .68$). Post hoc analysis revealed a decrease in ML sway irregularity (ie, decreased ApEn values) in the previously concussed group as the postural-control task difficulty increased. The ML sway irregularity of the nonconcussed group increased (ie, increased ApEn values) as the postural-control task difficulty increased. Additionally, the previously concussed group had more irregularity (ie, greater ApEn values) in conditions 1 through 3 and less irregularity in conditions 5 and 6 than did the nonconcussed group (all P values $< .05$).

The analysis between postural control and time since injury revealed no significant correlations (all P values $>$

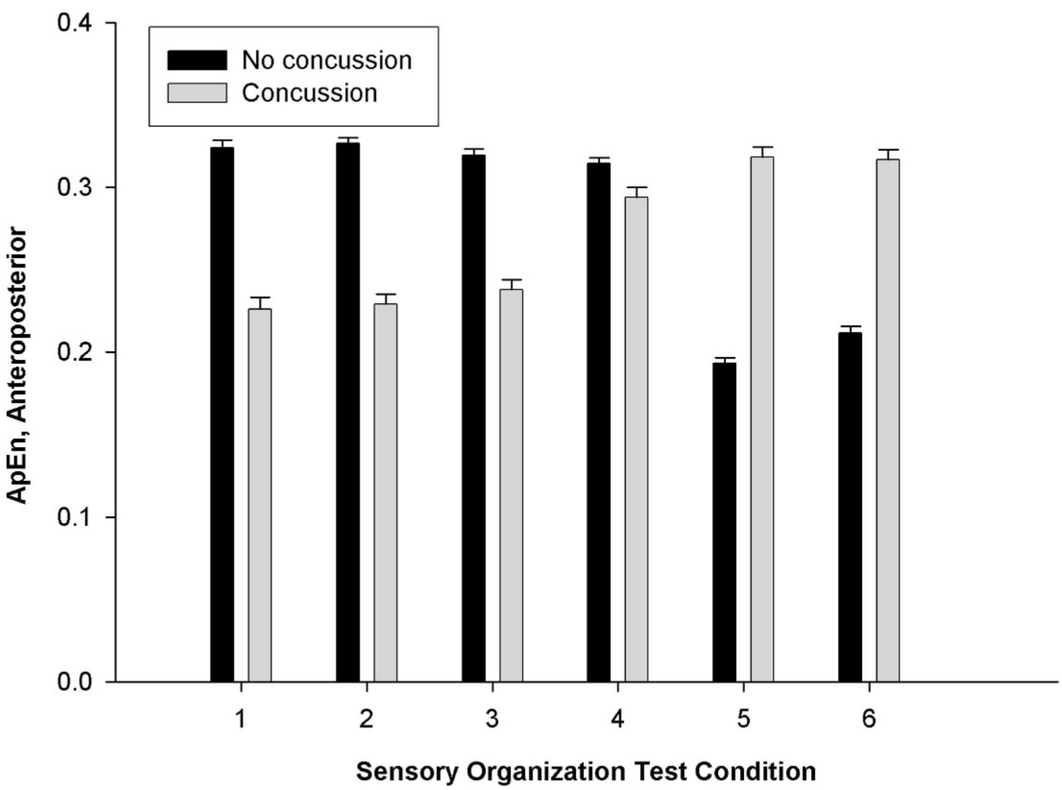

Figure 2. Approximate entropy (ApEn) of anteroposterior center-of-pressure excursions as a function of condition and concussion group.

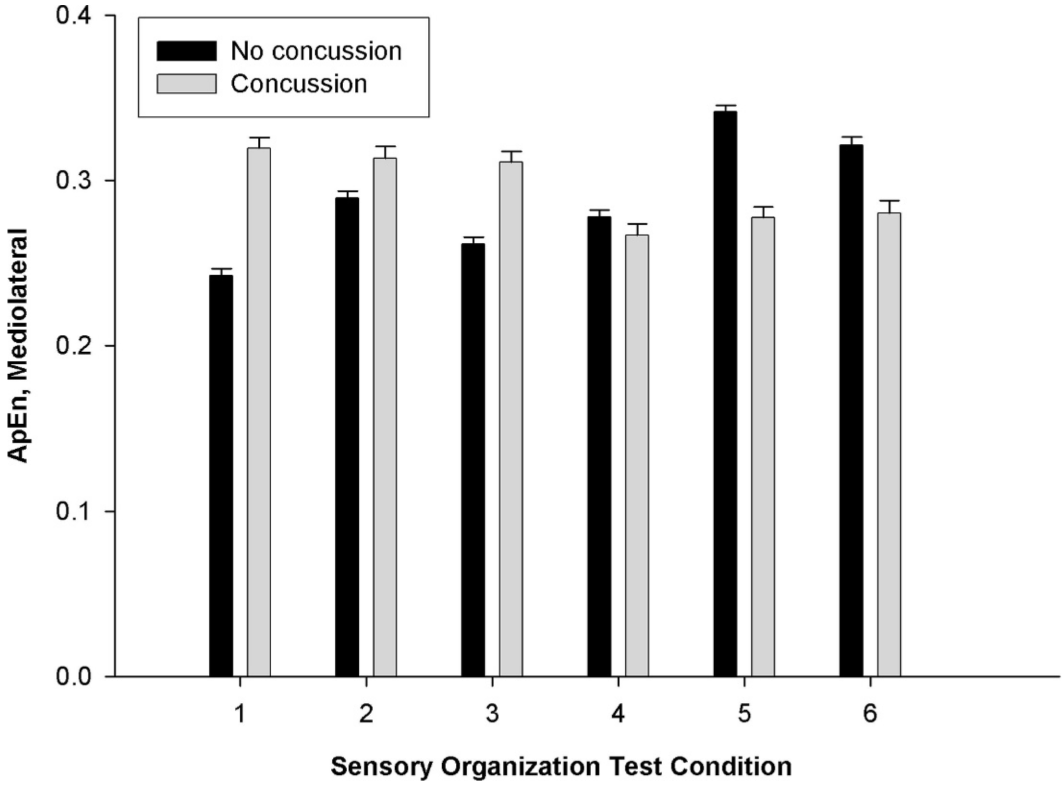

Figure 3. Approximate entropy (ApEn) of mediolateral center-of-pressure excursions as a function of condition and concussion group.

.05). As such, no evidence supported the notion that time since concussion influenced the results within the population under investigation.

DISCUSSION

Our purpose was to determine if a history of mTBI results in persistent changes in one's ability to maintain an upright stance. The most important findings are the presence of significant task-dependent alterations in postural dynamics in those with a history of mTBI in the absence of functional postural-control changes. Specifically, no difference was seen in 3 of the 4 functional-balance scores generated by the SOT between the previously concussed and nonconcussed groups. A difference was noted between the groups in the visual ratio score, but this difference did not appear to represent a meaningful clinical change. More notably, an evaluation of the postural-sway dynamics revealed task-dependent differences between groups. The previously concussed group increased their AP postural-sway irregularity as the postural task became more demanding. Under identical conditions, the nonconcussed group decreased their AP postural-sway irregularity. Examinations of ML sway revealed inverse results, with the nonconcussed group showing increasing postural irregularity and the previously concussed group showing decreasing postural irregularity as the postural challenge became more difficult.

Previous Concussion History and Traditional Measures of Postural Control

The method we used to evaluate postural control (ie, the SOT) is sensitive to acute changes in postural control after mTBI.[8,23–25] After a diagnosed mTBI, participants with a history of concussion demonstrated declines in the composite balance and visual and vestibular ratio scores.[8] These deficits are interpreted as evidence that previously concussed individuals have difficulty maintaining postural control. The deficiency has been linked to an inability to properly integrate sensory information pertinent to maintaining balance.[6] Examinations of traditional postural indexes revealed that these deficits follow a predictable recovery pattern, with most individuals returning to their premorbid level of performance within 3 days of injury.[6,8] Consistent with this view, minimal differences were noted in the SOT scores between nonconcussed and previously concussed participants. Although small differences in SOT values between groups (ie, visual ratio, the Table) were present, both groups demonstrated scores well above accepted norms, negating the potential clinical significance of this observation. Overall, these observations indicate that traditional techniques of balance assessment, such as the SOT, may not be sensitive to the persistent effects of concussion.

The lack of group differences in SOT measures draws into question the ability of the clinical balance assessments to readily detect deficits beyond the acute stage of injury. Thus, clinicians need to be aware of these limitations and realize that more sensitive measures of both static and dynamic balance may reveal clinically meaningful changes in postural control stemming from the persistent effects of concussion.

Previous Concussion History and the Dynamics of Postural Control

Unlike traditional measures of postural control, which estimate the amount of postural sway, nonlinear dynamical measures assess the time-dependent structure of postural control (ie, how postural control fluctuates over time). The nonlinear measure used in the current investigation, ApEn, provides an estimate of time-series (eg, postural-sway) predictability. A more predictable signal (ie, less irregular and lower ApEn values) is believed to result from fewer control processes and, hence, is less complex. Therefore, those with lower ApEn values have less ability to maintain postural stability. Cavanaugh et al[9] were the first to examine the effect of mTBI on postural-control dynamics. In a series of investigations applying ApEn to acute postconcussion postural-control assessments, they reported an increase in the structure of COP deviations up to 4 days after mTBI. Moreover, they found the adverse effect of mTBI on postural dynamics most pronounced in the ML direction,[24,25] congruent with our findings. Our results also extend the work of Cavanaugh et al[9] in demonstrating the differences between previously concussed and nonconcussed individuals beyond the 4-day timeline they examined.

The increase in postural-dynamics structure after mTBI is compatible with the loss-of-complexity hypothesis of aging and disease.[26] Within this theoretical framework, physiologic output, including neuromuscular output, results from the complex interplay of control processes (eg, visual-feedback loops, vestibular-feedback loops) operating in unique time scales. The interplay of multiple control processes results in a constantly fluctuating, intricate movement pattern. Any aberration in a single control process as a result of disease or injury decreases the system's output complexity (ie, neuromuscular output). Cavanaugh et al[24] suggested that a lower ApEn value during a postural-control task reflected less balance complexity. The decline is thought to have resulted from impaired functioning of the underlying processing loops responsible for postural control after mTBI.

Within the current investigation, previously concussed individuals did not exhibit an overall decrease in balance complexity across all conditions but rather exhibited differences in a task-dependent manner. These results are in contrast to the loss-of-complexity hypothesis but do support the predictions of the loss-of-adaptability hypothesis of aging and disease.[27,28] The loss-of-adaptability hypothesis maintains that task constraints (eg, environmental demands, such as availability of visual information) drive the dynamics of neuromotor output and that injured individuals are less able to constrain their output to task demands, resulting in suboptimal performance. The interaction between postural demands and concussion history is congruent with this hypothesis.

For instance, previously concussed athletes demonstrated increased postural-sway irregularity (ie, increased ApEn values) as the postural-control task increased in difficulty in the AP direction (Figure 2). However, nonconcussed athletes displayed decreased postural-sway irregularity (ie, decreased ApEn values) as the postural-control task increased in difficulty in the AP direction. As in the easier postural-control conditions, individuals with a history of concussion demonstrated less complex postural sway in the AP direction than did those without a history of concussion. The opposite finding is observed in the ML direction, with the previously concussed group having greater complexity in postural sway in the easier postural conditions but less complexity in the more difficult postural conditions (Figure 3).

The group differences in the dynamic structure of AP and ML COP excursions indicate that the previously concussed and nonconcussed groups applied different postural strategies during the balance task. As indicated by an increase in ApEn, the nonconcussed group seemed to increase its control in the ML direction, whereas the previously concussed group increased its control in the AP direction as postural demands increased. The association between suppressed ML postural control and falls[29] raises the possibility that individuals with a history of concussion may be at greater risk for falls. Further work is needed to examine this potential association.

Cognitive and motor decrements are well-established consequences of mTBI,[4,23] and declines in one area are believed to be associated with declines in the other area.[30] Prolonged postural-control deficits after concussion parallel the findings of persistent cognitive deficits after concussion,[31,32] bolstering the theory that mTBI should no longer be considered a transient injury without long-term effects on cerebral functioning. Our investigation was not intended to elucidate the underlying pathophysiology manifesting as persistent changes in postural-control complexity. However, we speculate that each mTBI results in subtle neurotrauma to areas of the brain that influence the overall postural-control mechanism. Balance decrements have been clearly demonstrated in the early days after insult,[11] but long-term, outwardly visible postural control is preserved through the plastic adaptation of alternative neural pathways. Functional magnetic resonance imaging analysis has shown such changes in concussed and nonconcussed athletes who perform equally on functional cognitive evaluations.[33] Whether these changes will ultimately result in deficits that have functional implications may depend on numerous factors, such as number and severity of injuries, age, and activity level.

Limitations

Although our results parallel those of others suggesting that mTBI may result in persistent changes in cognitive functioning, the findings are limited by the self-reported concussion histories and cross-sectional retrospective design. Thus, caution should be taken when interpreting the results. Ideally, an examination of persistent alterations in postural control after concussion requires a longitudinal study design. Our findings do support, however, the need for longitudinal research in concussed individuals. We also relied on the participants to accurately identify the number of concussions sustained before testing. It is possible that some athletes in the nonconcussed group may have actually suffered concussions, because some concussions go unreported and undiagnosed.[3] The high percentage of individuals with a previous concussion (28.2% of the sample) makes this possibility less likely.

CONCLUSIONS

Traditionally, mTBI has been thought to result in short-lived impairment to postural control and neurocognitive functioning.[34] Many individuals outwardly recover rapidly from this injury in a matter of days, but this investigation supports the growing literature demonstrating that changes in cerebral functioning, including postural control, may persist long after acute injury resolution. The clinical evaluation of our young adult cohort yielded no difference between those with and without an mTBI history.

Subtle differences revealed in this investigation became apparent only through in-depth analysis using emerging analytical techniques and technologies. How these subtle deficits in balance apply to functional balance performance and the recovery and return to play of acutely injured athletes is not entirely clear. Future research using longitudinal designs is needed to clarify the relationship between the subtle postural-control deficits noted here and functional balance performance.

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