Relationship between changes in vestibular sensory reweighting & postural control complexity

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Abstract:

Complexity measures have become increasingly prominent in the postural control literature. Several studies have found associations between clinical balance improvements and complexity, but the relationship between sensory reweighting and complexity changes has remained unobserved. The purpose of this study was to determine the relationship between sensory reweighting via Wii Fit balance training and complexity. Twenty healthy adults completed 6 weeks of training. Participants completed the sensory organization test (SOT) before and after the sessions. Complexity of postural control was analyzed through sample entropy of the center-of-pressure velocity time series in the resultant, anterior–posterior (AP), and medial–lateral directions, and compared to SOT summary score changes. Significant differences were found between pre- and post-training for the condition five ($p < .001$, $d = .525$) and vestibular summary scores ($p < .001$, $d = .611$). Similarly, changes in complexity were observed from pre- to post-training in the resultant ($p = .040$, $d = .427$) direction. While the AP velocity was not significant ($p = .07$, $d = .355$), its effect size was moderate. A moderate correlation was revealed in the posttest between AP complexity and condition 5 ($r = .442$, $p = .05$), as well as between AP complexity and the vestibular summary score ($r = .351$, $p = .13$). The results of this study show that a moderate relationship exists between postural control complexity and the vestibular system, suggesting that complexity may reflect the neurosensory organization used to maintain upright stance.

Keywords: Complexity | Postural control | Entropy | Sensory organization test

Article:

Introduction

Complexity-based metrics have become an increasingly common tool to analyze postural control over the last two decades (van Emmerik et al. 2016). Since the introduction of the loss of complexity hypothesis (Lipsitz and Goldberger 1992), researchers have uncovered patterns in the “noise” of postural control (Manor and Lipsitz 2013). This noise has since been observed to be a natural variability within the system that may reflect the ability to maintain posture throughout changing conditions. Complexity measures describe how this natural variability within the postural control system is structured throughout time. It is theorized that this variability is the result of numerous interactions occurring throughout the body that contribute to functional movement. In terms of postural control, the integration and weighting of sensory information within the central nervous system (CNS) appear to be two interactions of the upmost importance in the maintenance of an upright stance (Horak 2006; Peterka 2002). Sensory integration is generally thought of as the process by which sensory information is collected and centralized by the CNS. Following that, the CNS gives the information it believes to be accurate and reliable priority (greater attention) to complete a certain task (e.g., postural control). This shift toward more accurate and reliable information is also called sensory reweighting.

It is important to note that the weighting of sensory information is not static. Rather, it is dependent on external and internal information that is available, as well as the person’s ability to integrate the information (Assländer and Peterka 2014). Specific to postural control, this includes sensory information from the vestibular, visual, and somatosensory systems (Peterka 2002). The ability of humans to reweight sensory information has been consistently shown throughout the literature (Nashner 1982; Oie et al. 2002, Peterka and Loughlin 2004; Shumway-Cook and Woollacott 2000). Literature in this area has provided insight into the flexibility of the neuromotor control (i.e., how much sensory reweighting is possible), as well as highlighting typical changes that occur due to age or pathology. The integration and reweighting behaviors of postural control are commonly demonstrated through center-of-pressure (COP) analyses (Peterka 2002; Shumway-Cook and Woollacott 2000; Teasdale and Simoneau 2001; Vuillerme et al. 2001). Over the past several years, the sensory organization test (SOT) has become an increasingly used COP-based assessment to measure sensory integration and reweighting.

The SOT assessment isolates contributions from the sensory systems through removal of visual information via eyes closed, or by using sway-referenced surround and force plate (Fig. 1). The term “sway-referenced” indicates that both the surround and force plate have the ability to tilt in the anterior–posterior (AP) direction in response to a change in the individual’s COP. This causes inaccurate sensory information to be integrated by the CNS, forcing an individual to reweight the contribution of information from each system to remain upright. Each condition of the SOT gets progressively harder as it eliminates or distorts certain sensory contributions. For example, condition three involves the activation of the sway-referenced surround that will shift in the AP direction in response to the participant’s postural sway. This effectively causes a discrepancy between what the visual system sees (no change in depth perception) and what it is expecting to see (change in depth perception). A healthy individual will reweight so that accurate information from unaffected systems is given priority. Several high fall-risk populations (e.g., older adults, Parkinson’s disease, stroke) have shown an inability to alter their sensory contributions as the environment changes and are thus more likely to incur a fall (Bonan et al. 2004; Brown et al. 2006; Cohen et al. 1996; Di Fabio and Badke 1990). Thus, interventions designed to reweight the sensory system in fall-risk populations have shown promise (Bugnariu and Fung 2010; Haran and Keshner 2008; Hu and Woollacott 1994; Yen et al. 2011).

FIGURE 1 IS OMITTED FROM THIS FORMATTED DOCUMENT

Fig. 1 Six conditions of the sensory organization test on the NeuroCom balance master

Similarly, researchers have observed “unhealthy” COP complexity behaviors during quiet stance in populations at high fall-risk—typically described as weaker (i.e., less complex) patterns in the COP time series (Donker et al. 2007; Fournier et al. 2014; Manor et al. 2010; Seigle et al. 2009; Vaillancourt and Newell 2000). These measurements have been inferred to be indicative of an individual’s adaptive capacity when perturbed. Adaptive capacity, in the context of postural control, can be defined as an individual’s ability to stay upright when exposed to various external and/or internal disturbances. This has been shown in the literature through comparisons of complexity between populations at lower and higher fall-risk (Duarte and Sternad 2008; Ihlen et al. 2016; Kang et al. 2012; Manor et al. 2010). Postural control complexity interventions have revealed that these processes are plastic and improvement of these measures closely correlate to functional improvements (Costa et al. 2007; Lough et al. 2012).

However, we are unaware of previous work examining how changes in an individual’s ability to integrate and reweight sensory information may alter their postural control complexity. The purpose of this study was to determine to what extent a relationship between sensory integration/reweighting and postural control complexity might exist in a healthy individual. Such a relationship would suggest that sensory information processing in the CNS is either related to or is a potential mechanism of the variability patterns seen in postural control complexity. This finding would support the creation of time- and cost-efficient tools (e.g., smartphone applications) that can detect differences in complexity from sensory-based balance interventions. To accomplish this, we performed a secondary analysis on data available from a Wii Fit balance training study (Cone et al. 2015). The original study observed the changes in summary scores from the SOT from the pre- to post-training balance assessments, indicating that sensory reweighting occurred with balance training. This current study compared those results to complexity measurements derived from the raw COP data. With this comparison, we were able to observe how changing an individual’s sensory reweighting might related to their postural control complexity. Our hypotheses were twofold: (1) A significant increase in complexity would be observed from the pre- to the post-training SOT assessment only in condition five of the SOT (based on the results from Cone et al. 2015), and (2) there would be a moderate-to-large correlation between complexity and condition five of the SOT. Since the vestibular score is derived from condition five, it was also hypothesized that a moderate-to-large correlation would be observed between postural control complexity and the vestibular score. Data supporting these hypotheses would indicate that postural control complexity is modifiable and positively associated with the ability to maintain upright stance.

Materials and methods

Participants and apparatus

Twenty healthy adults (23.4 ± 3.8 years) participated in this study. All participants had no cardiovascular, musculoskeletal, or neurocognitive disorders. Participants were required to be free of pain and/or injury to the lower extremity/back for at least 6-months prior to, and throughout, the study. The local institutional review board approved this study, and all participants signed a written consent before study protocol began.

The NeuroCom balance master (Neurocom International Inc., Clackamas, OR, USA) is a computerized dynamic posturography system that specializes in identifying possible contributions and/or deficits of physical and sensory processes (Mancini and Horak 2010; Visser et al. 2008). It was designed to conduct the SOT and provide preliminary clinical analyses on an individual's sensory abilities. The entire SOT (six conditions) was conducted for the original study from which this secondary data analysis is derived (Cone et al. 2015). This includes the following conditions: (1) eyes open with no perturbation, (2) eyes closed with no perturbation, (3) eyes open with sway-referenced surround, (4) eyes open with sway-referenced force plate, (5) eyes closed with sway-referenced force plate, and (6) eyes open with sway-referenced surround and force plate (Fig. 1). Each condition consisted of three trials, with each trial lasting 20 s (total of 18 trials).

Raw and summary data were recorded for each trial and exported. Raw data included the COP displacement in the anterior–posterior (AP) and medial–lateral (ML) directions collected at a sampling rate of 100 Hz. Summary data included the average score for each condition, as well as scores for individual sensory systems (i.e., vestibular, visual, and somatosensory) and a summary score. The NeuroCom algorithm for summary scores assumes that an individual's maximal range of motion in the AP direction is 12.5°, with $\theta(A)$ equal to the maximum anterior displacement and $\theta(P)$ equal to the maximum posterior displacement.

The NeuroCom SOT summary measurements are calculated as follows:

$$\textbf{SOT score} = 100\{12.5 - [\theta(A) - \theta(P)]\}/12.5$$

Procedure

After signing the written consent, participants completed the SOT protocol. First, the participants put on a safety harness that was attached to the NeuroCom to ensure that no injurious falls would occur during the assessment. Next, the investigator moved the participant's feet into the proper stance width that was determined by their height (short, medium, or tall). This was standardized according to the NeuroCom's guidelines in the manual (58, 64, 70 in.). Once situated, the investigator briefly described the assessment and instructed the participant to look straight ahead at all times and maintain a normal posture. SOT trials were semi-randomized, with an audible tone indicating when a trial began and ended.

Once pretraining NeuroCom testing was completed, participants began Wii Fit (Nintendo Co. Ltd., Kyoto, Japan) balance training within 3 days. All balance training was derived from the Wii Fit Plus program's balance section. This required the use of a Wii Fit balance board, "Wii-mote" controller, Wii Fit Plus game disc, and a 42-inch television. Only seven of the "mini-games" from the Wii Fit Plus were played for the intervention including: balance bubble, penguin slide, ski slalom, snowboarding, soccer heading, table tilt, and tightrope. These were all chosen due to the difficulty and range of motion required to play. All games required the participants to move their avatars' bodies via changes in their COP. The Wii balance board has four force transducers that detected change in COP, which has been shown to have high reliability and validity compared to a NeuroCom force plate (Chang et al. 2013).

The 6-week intervention consisted of 18 individual sessions of Wii Fit play. Each session lasted about 45 min, and two to four sessions were held per week. An investigator was always in the room to ensure that participants played all games each week. Participants were allowed to progress to more difficult levels as they showed consistent improvement. The post-training SOT assessment was performed identical to the pretraining assessment and was completed within 3 days from the end of the balance training. We conducted a secondary analysis of NeuroCom SOT data that was originally collected to observe how a 6-week Wii Fit balance training regimen affects sensory contributions to postural control (Cone et al. 2015).

Dependent variables and data analyses

Customized MATLAB (Mathworks, Natick, MA, USA) scripts were utilized in order to calculate the resultant, AP, and ML COP velocities from the raw COP displacement (both x and y directions) data. These raw data were recorded from the signal obtained from the NeuroCom's force plate. COP velocity was selected as the dependent variable over COP displacement due to the latter's tendency to be nonstationary, which can be a problem with some complexity measures (Bollt et al. 2009; Ramdani et al. 2009). To measure the complexity of the postural control system, sample entropy (SampEn) was used. SampEn measures the regularity of a time series by determining the probability that a pattern within a time series will repeat, excluding self-matches. Values for SampEn will increase as a less regular behavior is observed. Thus, an increase in the SampEn value indicates an increase in complexity (Pincus 1991; Richman and Moorman 2000). To optimize the algorithm, we set the pattern/template length m to 2 points and the radius of acceptable values r to .22 * standard deviation after following the previous guidelines (Lake et al. 2002). All complexity data utilized the raw velocity data sampled at 100 Hz (2000 data points per trial). SampEn values were averaged across trials to give a single value per condition for each individual. This was done in order to match the summary data. Variables of interest from the summary data included both condition and sensory scores from the SOT.

To address hypothesis one, postural control complexity data in each direction (resultant, AP, and ML) were compared between pre- to post-training using paired t tests. To address hypothesis two, bivariate correlations were conducted between the postural complexity data and SOT scores in each direction. The Pearson product-moment correlation coefficient was used to measure all associations. Cohen's d effect sizes were also calculated. Alpha level was set at $p = .05$. SPSS version 22 (IBM, Armonk, NY, USA) was utilized for all statistical analyses.

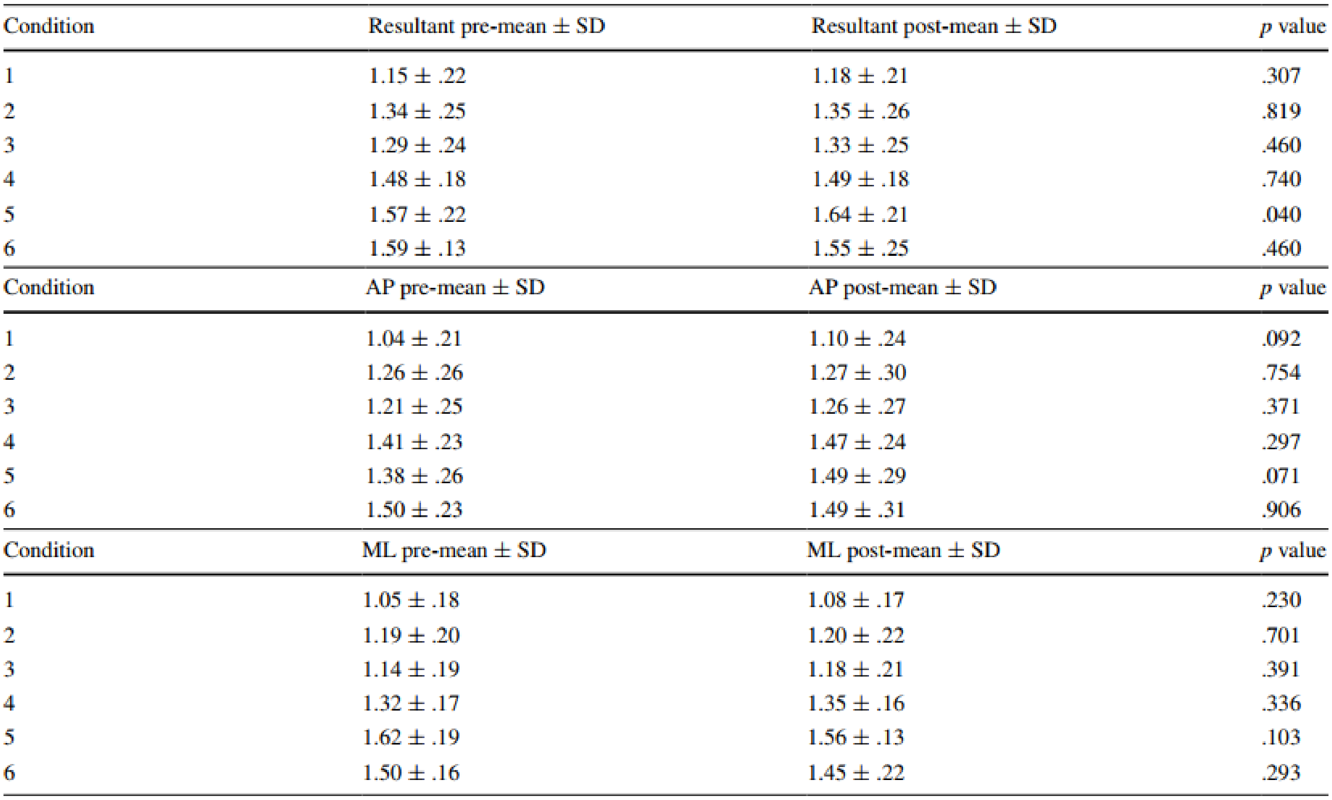
Results and discussions

Results

To address hypothesis one, postural control complexity data in each direction pre- and post-training are presented in Table 1. In the resultant direction, only condition 5 showed significant differences in postural control complexity from pre- to post-training, *t*(19) = 2.202, *p* = .040, *d* = .427). In the AP direction, a near-significant difference was observed in condition five, *t*(19) = 1.911, *p* = .071, *d* = .355) (Fig. 2).

Since postural control complexity only changed in the resultant and AP directions in condition 5 due to the training, those data were further examined to determine whether postural control complexity was associated with the condition 5 score (and the vestibular score) before and after training (hypothesis two). Before the training, no significant associations were observed (all *p* > .05). However, after the training, a moderate association was observed between postural control complexity in the AP direction and the condition five score (*r* = .442, *p* = .05), as well as a moderate association between postural control complexity in the AP direction and the vestibular score (*r* = .351, *p* = .13) (Fig. 3).

Table 1. Means and standard deviations of all dependent variables



Condition	Resultant pre-mean ± SD	Resultant post-mean ± SD	*p* value
1	1.15 ± .22	1.18 ± .21	.307
2	1.34 ± .25	1.35 ± .26	.819
3	1.29 ± .24	1.33 ± .25	.460
4	1.48 ± .18	1.49 ± .18	.740
5	1.57 ± .22	1.64 ± .21	.040
6	1.59 ± .13	1.55 ± .25	.460
Condition	AP pre-mean ± SD	AP post-mean ± SD	*p* value
1	1.04 ± .21	1.10 ± .24	.092
2	1.26 ± .26	1.27 ± .30	.754
3	1.21 ± .25	1.26 ± .27	.371
4	1.41 ± .23	1.47 ± .24	.297
5	1.38 ± .26	1.49 ± .29	.071
6	1.50 ± .23	1.49 ± .31	.906
Condition	ML pre-mean ± SD	ML post-mean ± SD	*p* value
1	1.05 ± .18	1.08 ± .17	.230
2	1.19 ± .20	1.20 ± .22	.701
3	1.14 ± .19	1.18 ± .21	.391
4	1.32 ± .17	1.35 ± .16	.336
5	1.62 ± .19	1.56 ± .13	.103
6	1.50 ± .16	1.45 ± .22	.293

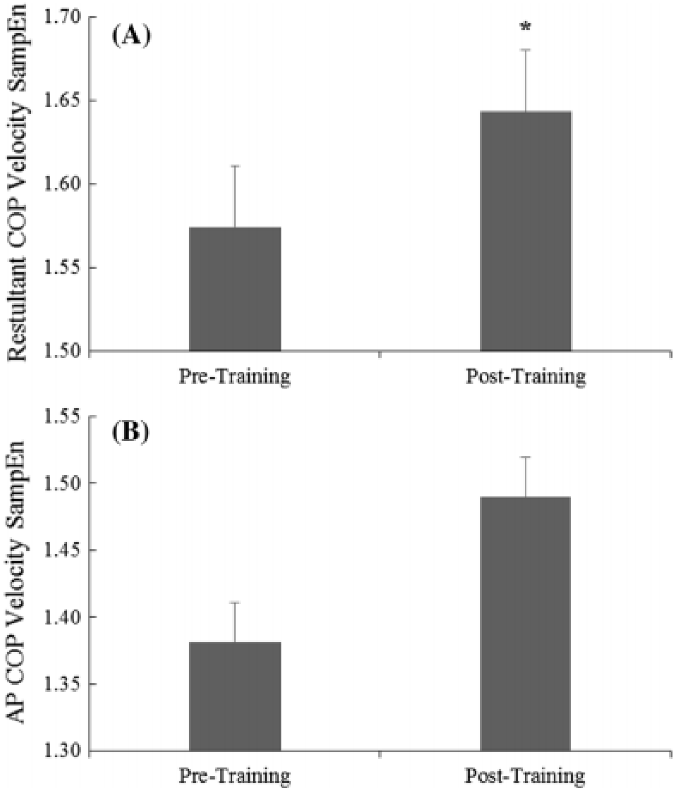


Fig. 2 Mean (±SE) change in COP velocity SampEn for SOT condition 5 in the resultant (a) and anterior–posterior (b) directions

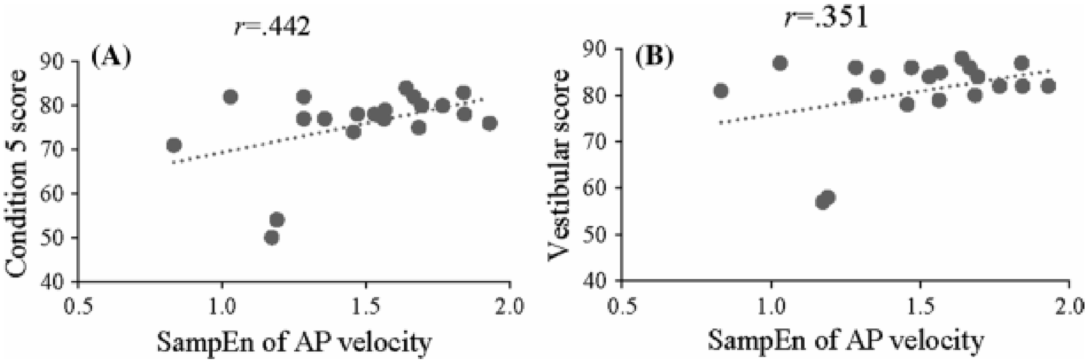


Fig. 3 Correlations between post-training AP velocity SampEn values the condition 5 score (a) and the vestibular score (b)

Discussion

The purpose of this study was to determine to what extent sensory reweighting and postural control complexity changes are related. To accomplish this, we conducted a secondary analysis of NeuroCom SOT data that were originally collected to observe how a 6-week Wii Fit balance training regimen affects sensory contributions to postural control. The current study compared the results observed within that study to the changes in COP velocity complexity. Consistent with the previous study, increased values of resultant and AP directions were observed from pre- to post-training in condition five (this time with respect to complexity), with both variables showing that the participants' changes had moderate-to-large effect sizes. Moderate associations were also observed between the AP complexity and summary scores. Only small, insignificant associations were found between the resultant and summary scores.

Condition five is regarded as the vestibular condition within the SOT due to its removal of visual information (eyes are closed) and inaccuracy of the somatosensory input (sway-referenced platform) (Nashner et al. 1982). The vestibular summary calculation is a relative scoring of condition five over condition one (baseline). Similar vestibular reweighting effects have been shown in other virtual reality training programs (Yen et al. 2011; Di Girolamo et al. 1999). However, this is the first study to suggest that an exer-game or virtual reality balance intervention can cause both sensory reweighting and postural control complexity changes within individuals. Furthermore, observing such results demonstrates the both sensory reweighting and complexity are similarly modifiable in healthy adults, suggesting that complexity may reflect the neurosensory organization used to maintain upright stance. Thus, populations who are at a high fall-risk—who have been shown to have lower complexity—may benefit from balance interventions designed to reweight sensory information. It is also plausible that postural control complexity could be used as a marker for neurosensory reorganization. However, the latter statement would need to be systematically tested.

The observed results suggest that CNS reweighting of the vestibular system and postural control complexity may improve due to similar training mechanisms. Previous findings have observed that complexity is affected by the six conditions of the SOT, with condition five forcing the system into a less complex behavior in COP displacement due to its difficulty (Riley and Clark 2003). This is interesting to note, as we observed an opposing trend suggesting that COP velocity complexity increased in the more difficult conditions. One possible explanation is that the individuals who have trained with the Wii Fit are employing non-regular exploratory movements similar to those used during the intervention to stay balanced. While our SampEn scores have interesting implications on how the SOT's sensory challenges might affect postural control complexity, it is fascinating that only a specific task was significantly improved with training (as evidenced by the increase in condition five scores), which was paralleled with the only significant increase in COP complexity.

The training program required the participants to control and maneuver their COP in various directions and patterns to accomplish each game-specific task. These tasks required various timing and magnitude shifts that induce novel movement patterns within quiet stance, such as shifting COP repeatedly in the AP and ML directions (e.g., skiing and snowboarding games). This may have allowed for the postural control system to learn novel, adaptive patterns that increased its ability to restabilize from perturbations. A complex system is thought of as an adaptive system because it represents the system's ability to use a variety of strategies to maintain stability (e.g., movement patterns). Thus, the complexity/flexibility of the postural control system improved its ability to adapt to the condition five perturbations.

Similarly, the training program constantly challenged the vestibular system, as the participants' heads were constantly moving in various directions. This would cause a continuous stimulus for the otolith and canal systems that regulate vestibular input to the CNS. As the systems adapted to the training program, they could have become more sensitive at detecting movements of the head (lower sensory threshold) and send more accurate input to the CNS. Thus, the reweighting would have improved due to the increase in accurate information from the vestibular system. Conversely, it can also be argued that the CNS's ability to process the vestibular input might have improved as a greater amount of input was sent due to the constant stimulus.

Further, the data suggest that CNS reweighting of the vestibular system and postural control complexity becomes more coupled after the training program. Indeed, the moderate association observed between the AP velocity complexity and vestibular scores shows that by changing an individual's ability to reweight their sensory input, there is a greater likelihood of changing their overall complexity in upright stance during such perturbations. This study supports the findings of previous research showing that an alteration in complexity is associated with function across multiple systems, and specifically that sensory decrement/improvement is associated with postural control complexity (Costa et al. 2007; Lough et al. 2012; Manor et al. 2010; Manor and Lipsitz 2013). As the summary scores were calculated with information solely from the AP axis, it is logical that only AP complexity would be associated with the summary score changes observed from pre- to post-training. While this study does not provide causal evidence, it does suggest that changes in postural control complexity and sensory reweighting are similarly linked to balance performance.

While using young, healthy adults as participants to show improvements in postural control is uncommon for a training study, it reduced the possible confounding variables responsible for the improvements observed. Young, healthy adults have been shown to have greater complexity and sensory reweighting abilities than other ages and populations (Cohen et al. 1996; Costa et al. 2007; Kang et al. 2009; Roerdink et al. 2006). Thus, this study is a strong indicator of the possible relationship between these two processes. On the surface, it may appear that comparing the delta scores for our dependent variables between the pre- and post-training sessions would be a plausible way to examine the relationship between postural control complexity and balance ability via condition five and the vestibular summary scores. However, it is likely that postural control complexity and balance summary scores operate on different time scales, potentially making the correlation between the two metrics nonsignificant (both statistically and practically). Thus, examining their association at the pretest and posttest sessions independently provides a snapshot of their association, but not how they change over time in parallel. Future work should focus on identifying the time scales in which postural control complexity metrics change with training and how that change is associated with functional balance scores. Further, a next step in this line of research should be to investigate whether similar results are found when training clinical populations with similar balance interventions. As several processes within the CNS are hypothesized to relate to the system's complexity, this area of the literature is ripe for investigation of the mechanisms underlying complexity. Lastly, changes in muscle tissue due to training should be accounted for when examining changes in postural control complexity after a balance intervention to determine the role of muscle stiffness in enhanced balance control.

In conclusion, these findings provide support the notion that the sensory reweighting processes of the CNS are related to the postural control system's complexity in certain situations. This notion is supported by the positive correlations between the postural complexity and condition five scores, as well as the vestibular summary scores. While this is a significant step forward, more observations in high fall-risk populations are required to further understand how this knowledge can be applied to fall-prevention programs.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflict of interest.

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