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original research

Response to Tendon Vibration Questions the Underlying Rationale of Proprioceptive Training

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Context: Proprioceptive training on compliant surfaces is used to rehabilitate and prevent ankle sprains. The ability to improve proprioceptive function via such training has been questioned. Achilles tendon vibration is used in motor-control research as a form of proprioceptive stimulus. Using measures of postural steadiness with nonlinear measures to elucidate control mechanisms, tendon vibration can be applied to investigate the underlying rationale of proprioceptive training.

Objective: To test whether the effect of vibration on young adults' postural control depended on the support surface.

Design: Descriptive laboratory study.

Setting: Research laboratory.

Patients or Other Participants: Thirty healthy adults and 10 adults with chronic ankle instability (CAI; age range = 18–40 years).

Intervention(s): With eyes open, participants stood in bilateral stance on a rigid plate (floor), memory foam, and a Both Sides Up (BOSU) ball covering a force platform. We applied bilateral Achilles tendon vibration for the middle 20 seconds in a series of 60-second trials and analyzed participants' responses from previbration to vibration (pre-vib) and from vibration to postvibration (vib-post).

Main Outcome Measure(s): We calculated anterior-posterior excursion of the center of pressure and complexity index derived from the area under multiscale entropy curves.

Results: The excursion response to vibration differed by surface, as indicated by a significant interaction of $P < .001$ for the healthy group at both time points and for the CAI group vib-post. Although both groups demonstrated increased excursion from pre-vib and from vib-post, a decrease was observed on the BOSU. The complexity response to vibration differed by surface for the healthy group (pre-vib, $P < .001$). The pattern for the CAI group was similar but not significant. Complexity changes vib-post were the same on all surfaces for both groups.

Conclusions: Participants reacted less to ankle vibration when standing on the BOSU as compared with the floor, suggesting that proprioceptive training may not be occurring. Different balance-training paradigms to target proprioception, including tendon vibration, should be explored.

Key Words: ankle sprain, chronic ankle instability, balance, postural control, BOSU, foam

Key Points

- Young adults increased their postural sway in response to Achilles tendon vibration when standing on the floor and on foam.
- Young adults reduced their postural sway in response to Achilles tendon vibration when standing on a BOSU ball.
- Different balance-training paradigms to target proprioception, including tendon vibration, should be explored.

Standing exercises on unstable and compliant surfaces[1] such as memory foam or a Both Sides Up (BOSU) Balance Trainer (Hedstrom Fitness, Ashland, OH)[2] are commonly included in sport rehabilitation to improve balance.[3–5] With compliant-surfaces training, often referred to by clinicians as *proprioceptive training*, athletic trainers and physical therapists attempt to challenge postural control and to specifically address deficits in the integration of proprioceptive input for postural control.[4] Such training is commonly used with athletes after initial and repeated ankle sprains (chronic ankle instability [CAI]) because repeated ankle sprains are associated with peripheral impairments in joint position sense[1,6] and central deficits in proprioceptive integration.[7] Although a reduction in the recurrence of sprains[1,3] and improvements in balance and sport performance have been reported in the literature after proprioceptive training,[3] its ability to truly enhance proprioceptive input and processing in healthy individuals or those with CAI has been questioned.[8]

Postural control is a perceptual-motor process that includes the (1) sensation of position and motion from the visual, somatosensory, and vestibular systems; (2) processing of that sensory information to determine orientation and movement; and (3) selection of motor responses that maintain or bring the body into equilibrium.[9] The neuroscience literature often explains the process of sensory integration for postural control via sensory weighting and reweighting.[10] According to this perspective, a healthy sensorimotor system will select the most efficient sensory cue to attend to and decrease the weight of or attention to conflicting or confusing sensory cues. As viewed through this lens, unstable and compliant surfaces are sources of somatosensory confusion, which will lead healthy individuals to decrease their reliance on somatosensory cues and to increase their dependence on visual and vestibular information. This perspective is applied clinically, for example, in the Sensory Organization Test[11] and the Clinical Test of Sensory Interaction for Balance.[12] During the Sensory Organization Test moving-platform and the Clinical Test of Sensory Interaction for Balance foam conditions, a participant's balance performance is thought to reflect the ability to integrate mostly visual and vestibular information because the information from the surface is unreliable.

The sensory-weighting theory has been supported via studies[13–15] measuring the response of healthy individuals to a proprioceptive stimulus in the form of tendon vibration. Brief vibration of the calf muscles during standing in healthy young adults typically causes a backward sway[16] and increased postural sway as measured by center-of-pressure (COP) oscillations. This response, previously termed *vibration-induced falling*,[16] is mostly attributed to the muscle-spindle primary endings, which are known to be an important component of proprioception.[17] It is assumed that the vibration stimulus is erroneously interpreted as a stretch, leading to a contraction of the gastrocnemius and soleus muscles in response.[18] Vibration-induced falling may attenuate with various balance challenges. Ivanenko et al[13] tested 9 healthy young adults on a rigid platform and found that Achilles tendon vibration induced backward body sway, which then lessened when the platform tilted in the sagittal plane. Similarly, in young women, Spiliopoulou et al[14] observed increased body sway in response to Achilles tendon vibration during normal stance but not under challenging conditions such as tandem or single-legged stance. Kiers et al[15] extended these findings to a foam pad, showing that the COP velocity response to triceps surae vibration was reduced when young adults stood on foam compared with a stable surface with their eyes closed.

These results suggest that with respect to proprioception, a paradigm shift may be required regarding the role of unstable surfaces in sport rehabilitation or injury prevention. However, one important concept that was overlooked in previous studies was the level of challenge. When training athletes' postural control for preventing or restoring proprioceptive deficits, athletic trainers typically prefer a challenging exercise (such as stance on a BOSU ball) over an easier task (such as standing on memory foam or standing with eyes closed). To create a link between motor-control studies and their application in the field, we need to understand how a typical response to proprioceptive cues (ie, that of healthy young adults) changes as the challenge provided by the surface increases, using surfaces that are common in sports settings and testing individuals who may benefit from such training.

Ankle sprains are often perceived as simple and easy to treat, and people with repeated ankle sprains often continue to participate in sports.[19] Nevertheless, the high rates of repeated sprains and long-term disability reported in the literature suggest that CAI is not yet fully understood and a better understanding of prevention and treatment strategies is necessary.[20] We therefore wanted to explore whether the response of young adults with CAI was any different than the typical response of healthy young adults.

Traditionally, postural-control analysis relies on postural stability (ie, the ability to resist perturbations) and postural steadiness (ie, the ability to stand as motionless as possible) as indicators of balance control.[21] In this linear modeling, variability of the COP location during quiet standing is considered random error. A nonlinear-dynamics framework has been suggested to complement the traditional linear modeling. In this framework, COP oscillations are thought to contain a hidden structure that emerges in time, which may provide information regarding control mechanisms and adaptation to environmental constraints.[21] Nonlinear tools quantify the structure of variability of motor behavior over time; they ascribe higher values to a more-complex system (ie, a system displaying highly variable fluctuations in a physiological process). In postural control, adequate variability in COP oscillations is thought to help individuals adapt to personal, task, and environmental constraints.[22] Multiscale entropy (MSE), a nonlinear tool, was developed by Costa et al[23] to overcome limitations of previous nonlinear algorithms. Multiscale entropy is considered to be a sensitive measure of postural control in an impaired postural-control system that has been shown to be task dependent[24] and to display lower values with disease[25,26] (as a possible reflection of reduced degrees of freedom in the diseased system). The utility of MSE for athletic populations is currently unknown, as it has not been studied in healthy, active, young adults.

Therefore, our primary purpose was to test the postural-sway–excursion response of healthy young adults to a proprioceptive stimulus (Achilles tendon vibration) as the balance task became increasingly challenging (feet together on floor, feet together on foam, normal stance on a BOSU ball). We then explored whether young adults with a history of repeated ankle sprains and CAI responded any differently. For a comprehensive description of postural control, we also explored a nonlinear measure of postural sway (MSE). We asked whether the effect of vibration on postural excursion and postural-sway complexity depended on the surface on which participants (healthy young adults or young adults with CAI) stood. Given previous findings[13,14] of decreased reaction to vibration under challenging stance conditions, we hypothesized that the excursion response to vibration would decrease as the challenge induced by the compliant surface increased. Because MSE increased in the elderly during stance on wobble boards,[24] we anticipated an increase in complexity with attenuated response to vibration on the challenging surfaces. Finally, we expected participants with a history of repeated ankle sprains to demonstrate a decreased reaction to vibration because of their hypothesized proprioceptive deficits[1,27] but to display a similar pattern of attenuated response to vibration under increased challenge.

METHODS

Participants

We tested 30 healthy young adults (HEALTHY) and 10 young adults with CAI (CAI). For both groups, men and women of any race or ethnic background between the ages of 18 and 40 years with normal or corrected-to-normal vision were recruited. Participants assigned to the CAI group reported 3 or more sprains in the past 5 years, at least 1 of which was diagnosed as a moderate inversion ankle sprain, and at least 1 episode of the ankle giving way in the past 12 months.[28] Participants were excluded from the HEALTHY group if (1) they reported a lower limb or back injury within the 12 months before the study, (2) there was any evidence of somatosensory or vestibular loss, or (3) limited dorsiflexion (<10°) was found during a clinical screening. This study was approved by the university's institutional review board, and informed consent was obtained from all participants. We used 1 performance measure and 2 self-reported clinical measures to describe our sample: the single-legged conditions of the Balance Error Scoring System[29] (BESS; both groups), the Ankle Instability Instrument[30] (AII; CAI group only), and the Foot and Ankle Ability Measure[31] (FAAM; CAI group only).

Instrumentation

Twenty seconds of vibration were applied to both Achilles tendons of the participants through custom-designed vibration devices. The devices, always applied by the same researcher, were attached using elastic cuffs placed 4 cm above the calcaneal insertion of each Achilles tendon. To ensure comfort, the participants wore lightweight elastic sleeves underneath the cuffs. The root mean square amplitude of the applied vibration was measured by accelerometer to be 0.6*g* with a frequency of 80 to 85 Hz. Vibration-induced falling has been produced with frequencies ranging from 20 to 165 Hz.[16] A frequency of 80 to 85 Hz has been used previously and shown to produce larger responses than vibrations at slower frequencies.[32]

Testing Protocol

On a participant's first visit to our laboratory, we conducted a short demographic interview and a clinical screening, which consisted of clinical measures of balance,[29] vestibular and somatosensory senses, and ankle range of motion (see our companion paper[33] for further details on the clinical screening). During a second, longer session (up to 2.5 hours), participants were first introduced to the vibration and stance on the BOSU. They practiced stance on the BOSU for 1 to 2 minutes, were queried regarding their experience standing on the BOSU, and experienced the vibration stimulus for 20 seconds while sitting. Because we were interested in the interaction between vibration and a challenging environment, stance position on the floor and foam was conducted barefoot, with feet together to make the task more challenging for our sample of young and active individuals. However, pilot tests in our laboratory indicated that standing with feet together on the BOSU was not feasible for more than a few seconds; hence, we allowed participants to stand barefoot with feet hip-width apart on the BOSU. To ensure consistent foot placement between trials, we used adhesive tape to mark the heel position of the participant on the wooden plate and on the foam and to mark the medial sides of the right and left great toes when the participant was standing with feet hip-width apart on the BOSU. To ensure participants' safety, they wore a body harness attached to a ceiling hook and were guarded by a researcher, and two 4-point canes were placed at either side of the BOSU or foam for the participants to use as needed to mount the surface or to prevent a fall. Participants could place weight on the harness if they lost their balance, which happened only occasionally in the CAI group between BOSU trials. Otherwise, the harness was loose and the participants bore full weight.

We divided the conditions into blocks of test conditions and conducted 2 blocks of tests on each surface. The sequences of the blocks and of all conditions on a surface were randomized to prevent an order or a learning effect, but they were held constant among surfaces to allow for comparison. Each vibration condition lasted 60 seconds, was repeated 3 times per surface, and comprised 3 parts presented in the following order: 20 seconds of no perturbation (Pre), 20 seconds of continuous vibration (Vibration), and 20 seconds of no perturbation (Post). These data were part of a larger protocol that also included visual manipulation (participants' responses to the visual cues are reported elsewhere).[33] Therefore, participants stood in a darkened room and wore goggles that limited their peripheral vision. They were instructed to look at a screen placed 1 m in front of them and displaying white dots on a dark background. Visual manipulation and somatosensory manipulation (ie, vibration) did not occur during the same conditions. Here we report the findings from conditions involving tendon vibration only. Headphones playing a white-noise audio loop masked the sound produced by the vibrators (model Pulsar 590 Bluetooth headset; Plantronics, Inc, Santa Cruz, CA; model A320 Bluetooth transceiver; Jabra, Ballerup, Denmark; and model iPod Shuffle; Apple Inc, Cupertino, CA, containing the audio file).

Participants were asked to do whatever felt natural for them to maintain their balance. We then compared 3 levels of environmental constraints: (1) a wooden plate (floor), (2) high-density (96 kg/m^3; 10 × 36 × 36 cm) memory foam (foam), and (3) the compliant side of a BOSU ball. Each surface was placed on a multicomponent force platform (model 9281A11; Kistler, Zelený Pruh, Czech Republic) embedded in the floor. To maintain the viscoelastic properties of the foam, we replaced it after every 4 participants. The top of the wooden plate (5-cm high × 61 × 61 cm) matched the top of the BOSU (61 × 61 cm) and the bottom matched the smaller force platform (59 × 39-cm rectangle). This was done to ensure that all vertical forces were read by the force platform. In addition, 2 levels of organismic constraints were included: (1) history of repeated ankle sprains and (2) Achilles tendon vibration.

Data Reduction and Measurements

We sampled the COP signal at 100 Hz[24] and filtered it using a fourth-order low-pass Butterworth filter with a 5-Hz[34] cutoff frequency. Because of filtering artifacts, we eliminated the first 10 frames (0.1 seconds given the 100-Hz sampling rate) from analysis, and for consistency, we did that with each segment (Pre, Vibration, Post). We assessed the response to vibration in 2 ways. First, we used a traditional method, excursion (largest distance traveled in the anterior-posterior plane). We chose excursion, determined by the peak movement, because vibration-induced falling is normally a rapid, extreme motion.[35] This typical response to vibration can be seen in Figure 1, A through C. The test-retest reliability of anterior-posterior excursion was found to be good (intraclass correlation coefficient [ICC] = 0.75) in older adults standing on a stable surface when the mean of 3 trials was the outcome.[36] Construct

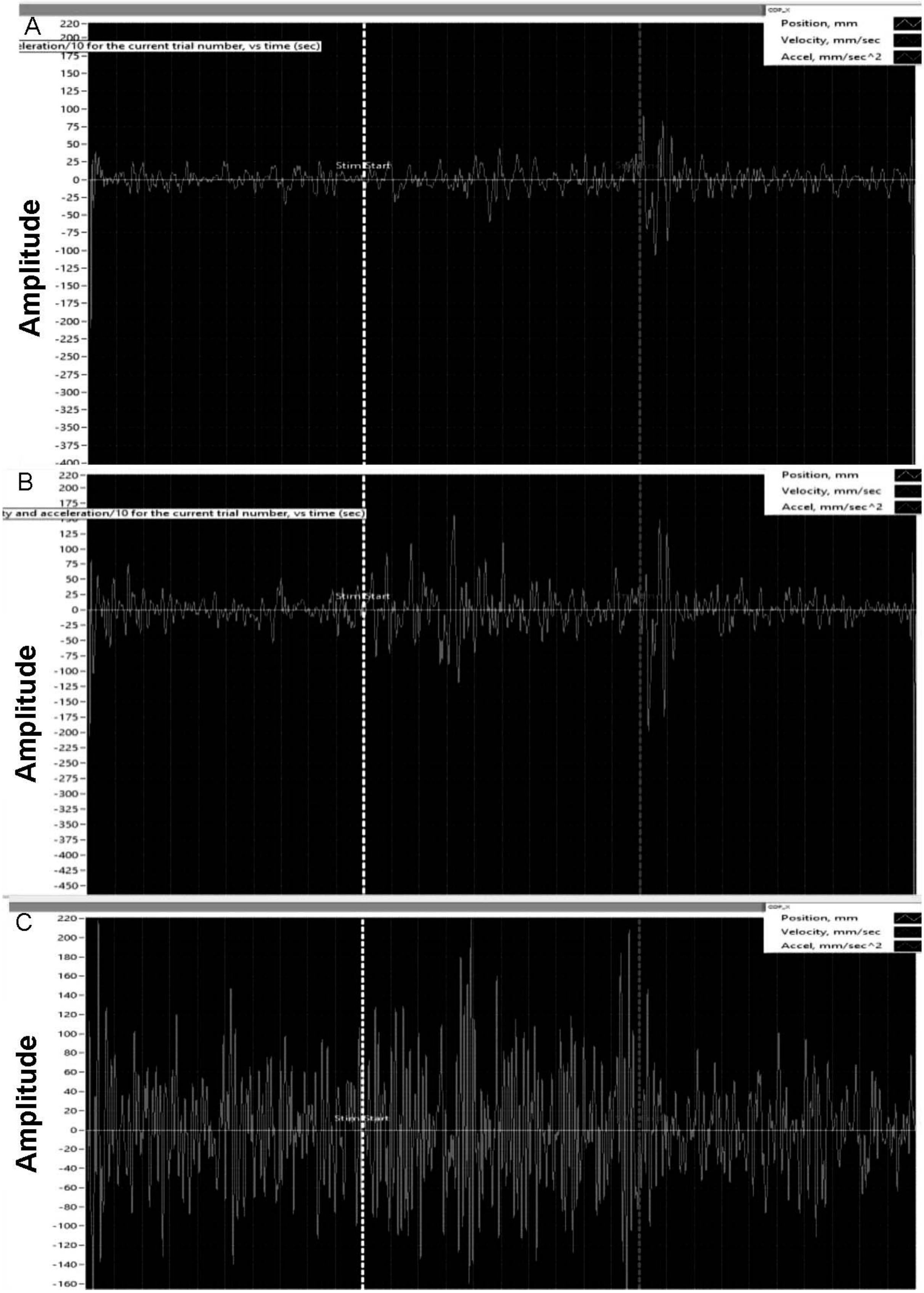

Figure 1. Three plots produced by our custom LabVIEW analysis program (National Instruments, Austin, TX) from a single trial of 1 participant. Data reflect anterior-posterior sway amplitude (mm; vertical axis) in response to vibration over time in seconds when the participant was standing on the A, floor, B, foam, or C, Both Sides Up Balance Trainer (BOSU; Hedstrom Fitness, Ashland, OH). Dashed longitudinal lines indicate onset (first vertical line) and termination (second vertical line) of the vibration stimulus. Note the peak in displacement immediately after the termination of vibration when the participant was standing on floor or foam. Also note an overall decrease in displacement postvibration on the BOSU.

validity was established by demonstrating a difference between fallers and nonfallers ($P < .001$).[36]

Second, we used MSE to quantify the degree of complexity in the fluctuations of a time series over multiple scale factors.[23] Briefly, MSE quantifies the regularity (or predictability) of a time series over varying time scales and is used to derive the complexity of a time series. For example, the position of a swinging ideal pendulum has low complexity because its position is very predictable over all time scales after a single cycle of motion is observed. A completely random time series (white noise) is also not considered complex as it has no structure other than randomness over all time scales. A complex signal exhibits structure (varying with the time scale) in what may otherwise appear to be a somewhat random behavior, such as sway. Multiscale entropy is a relatively new measure of postural control. Although several studies[26,37,38] have established its construct validity by demonstrating lower values with disease or injury and aging, reliability has not been reported. Given that, we tested the within-session repeatability in our data by calculating the ICC (1,1) (1-way random, absolute agreement). For HEALTHY, the ICCs ranged between 0.46 and 0.77 and were all significant at $P < .001$. For CAI, the ICCs were also good and ranged between 0.42 ($P = .02$) and 0.82 ($P < .001$) except for 1 condition (Foam, Post), where the ICC was very low (0.13), possibly because of minimal variability among people in this condition. We refer the reader to our companion paper[39] for further information regarding the background of MSE in postural-control research and changes in MSE with different balance challenges.

To calculate MSE, we constructed a coarse-grained time series by dividing the original time series into 8 nonoverlapping windows, called *scale factors*, of increasing length (parameter m). Scale 1 included all data points; on scale 2, every 2 data points were averaged; on scale 3, every 3 data points were averaged; and so on. For each coarse-grained time series, we calculated *sample entropy* (SampEn), defined as the negative natural logarithm of the probability that all pairs among $m + 1$ points are similar (the difference between them is smaller than the radius of similarity, r) given such similarity for m points. Consistent with the literature,[26] our chosen parameters were $m = 2$ and $r = 15\%$ of the standard deviation (SD) of the COP data. Because SampEn is stable across a wide range of parameters,[26] the choice of $m = 2$ allows for the greatest number of comparisons. We constructed MSE curves by plotting the SampEn per scale factor. The area under the MSE curve, that is, its integral, is the *complexity index* (complexity), which is the outcome measure used for analysis.[26] As recommended to justify the use of nonlinear analysis, we tested whether our data could be generated by uncorrelated random noise.[40] We shuffled the order of the data points[26] in each time period (Pre, Vibration, Post) using the Fisher-Yates[41] algorithm and compared the shuffled MSE results (complexity) with the original time series COP. This process is intended to show a distinction between real data and purely random data derived from the same set of data. By demonstrating no similarity between the 2, we determined that our data were not derived from a random source and instead represented real human behavior. Excursion and MSE were calculated in the anterior-posterior direction because vibratory stimulation of the Achilles tendon induces body sway mostly in the sagittal plane.[16]

Statistical Analysis

Demographic and clinical parameters were not normally distributed; hence, we compared those groups using the Mann-Whitney test for medians of numeric variables and conducted the Fisher exact test for categorical variables. We used visual display to explore differences in SampEn across scales for both groups. We constructed 2 separate 2-way repeated-measures analysis-of-variance models to test for the interaction between Pre to Vibration and surface (floor, foam, BOSU) and between Vibration to Post and surface. We chose to run 2 separate 2×3 models rather than one 3×3 to allow for a simpler, more meaningful interpretation of the interaction term in the model. The dependent measures (COP excursion and complexity) were represented in the model by the mean of the raw value obtained from 3 trials of the same condition. We conducted these analyses separately for both the HEALTHY and CAI groups. When the Mauchly test of sphericity was significant, we reported the P value of the Greenhouse-Geisser correction. If the interaction was not significant, main effects were reported. In the presence of a significant interaction ($P < .05$), the direction of the interaction was described. Descriptive information and 95% confidence intervals of the changes from Pre to Vibration and Vibration to Post per surface were also calculated for each group. We also computed the effect size using the Cohen d and Hedges g (a modification for sample size <20).[42] We chose to report the more-conservative Hedges g yet note that the estimates of effect size differed by no more than 0.01 for HEALTHY and 0.05 for CAI. Finally, to test the null hypothesis that our data were randomly derived, we calculated 24 paired t tests (4 conditions × 3 time periods × 2 groups) to compare the shuffled with the actual data and used a Bonferroni correction to set statistical significance at $\alpha = .002$ (0.05/24). Analysis was conducted using SPSS software (version 22; IBM Corp, Armonk, NY).

RESULTS

Sample

The groups were comparable on most demographic and anthropometric factors. Specifically, both groups consisted of 60% females and all but 2 participants in the HEALTHY group and all but 1 in the CAI group reported that they were exercising regularly. However, the groups differed in age (mean age ± SD: HEALTHY = 28.5 ± 5.4 years; CAI = 22.2 ± 4.6 years) and ethnicity (87% white in the HEALTHY group, 40% in the CAI group). Clinically, as expected, the CAI group performed significantly worse on the BESS,[29] measured as errors performed in a single-legged stance, with eyes closed, on the floor and on the foam on either leg (mean ± SD: HEALTHY = 8 ± 5; CAI = 14 ± 7; 0 is the best score, 40 is the worst). The BESS is sensitive to postural-control deficits in young adults with functional ankle instability.[43] Participants with CAI also completed the self-reported AII[30] and FAAM.[31] The mean ± SD *yes* response on the AII was 5 ± 2. The mean FAAM Daily score was 89% ± 7%, and the mean FAAM Sports score was 68% ± 21%. All 10 with CAI had positive

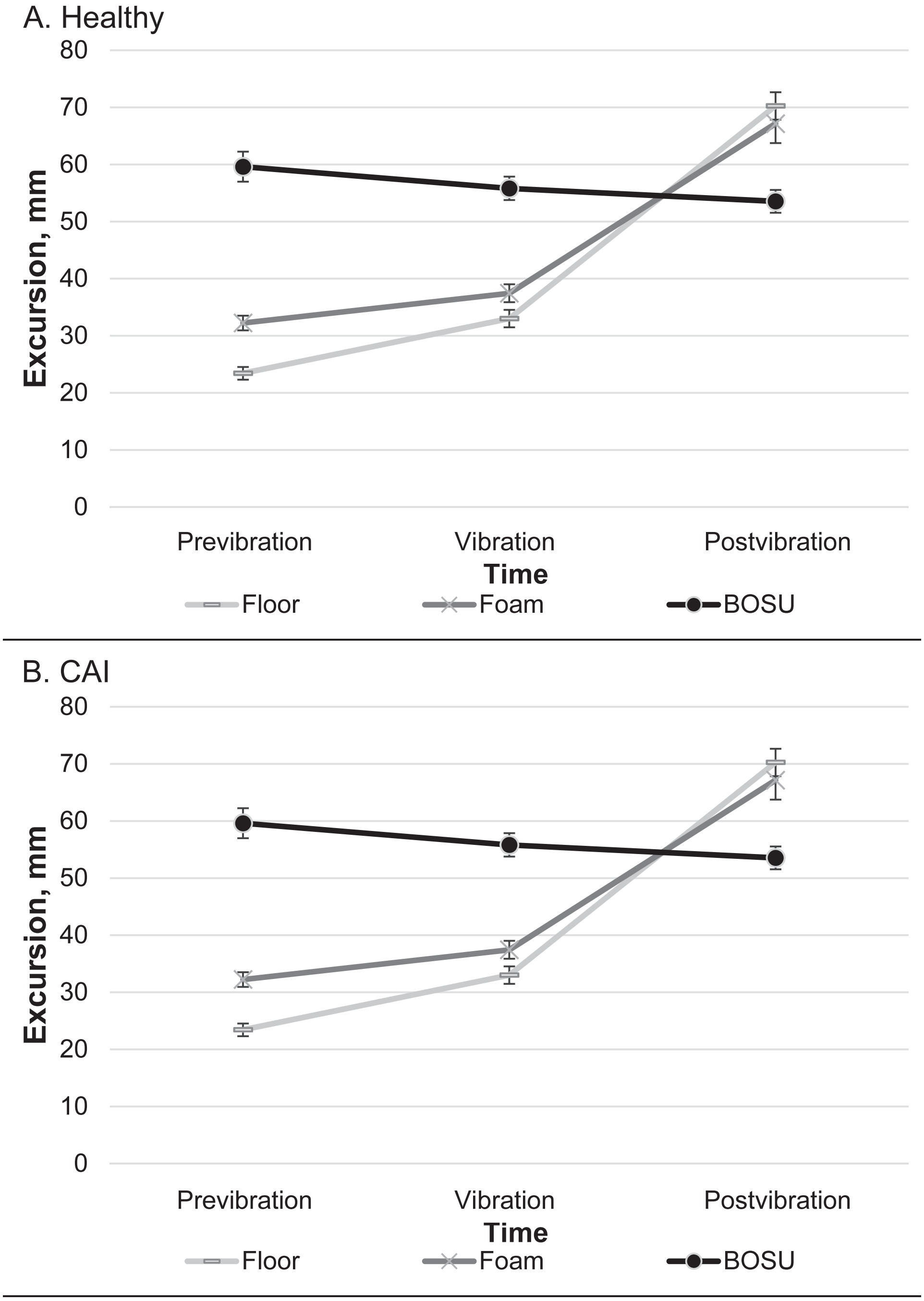

Figure 2. Maximal anterior-posterior excursion (mm; vertical axis) as a function of time in seconds previbration (PRE) and during (VIB) and after vibration (POST) across surfaces for A, healthy young adults and B, adults with chronic ankle instability (CAI). Error bars represent standard error of the mean. The HEALTHY group responded with an increase in excursion from PRE to VIB and from VIB to POST while standing on the floor, an increase of less magnitude while standing on the foam, and a decrease while standing on the Both Sides Up Balance Trainer (BOSU; Hedstrom Fitness, Ashland, OH). The CAI group demonstrated an increase in excursion from PRE to VIB and from VIB to POST while standing on the floor, a decrease in excursion PRE to VIB while standing on the foam, and a minimal response to vibration from PRE to VIB while standing on the BOSU with a decrease in excursion POST.

anterior-drawer tests (either weight bearing or non–weight bearing) and 8 had a positive talar tilt test.

Response to Vibration: Excursion

There was homogeneity of variances, as assessed by the Levene test for equality of variances ($P > .05$). Because the Mauchly test of sphericity was significant, a Greenhouse-Geisser correction was applied. Note that although excursion values are naturally higher on compliant surfaces (32 and 59 mm on the foam and BOSU, respectively, versus 23 mm on the floor for HEALTHY; Figure 2), the analysis focused on the interaction between surface and vibration. For HEALTHY, we found an interaction of Pre to Vibration and Vibration to Post ($P < .001$). The Hedges g showed a large effect size for the floor and foam (typically larger than 1) but a small effect for the BOSU (0.2–0.3). The CAI group displayed a slightly reduced excursion response to

Table 1. Changes in Anterior-Posterior Excursion (mm) by Surface and Group From Previbration to Vibration and Vibration to Postvibration

		Surface					
		Floor		Foam		BOSU	
Group	Time	Mean ± SD (95% CI)	ES	Mean ± SD (95% CI)	ES	Mean ± SD (95% CI)	ES
HEALTHY	Previbration-vibration	9.58 ± 9.58 (6, 13.15)	1.3	5.2 ± 7.28 (2.48, 7.92)	0.65	−3.8 ± 11.84 (−8.22, 0.62)	0.29
	Vibration-postvibration	37.24 ± 14.63 (31.78, 42.71)	3.35	29.7 ± 18.16 (22.92, 36.48)	2.02	−2.29 ± 11.27 (−6.5, 1.9)	0.2
Chronic ankle instability	Previbration-vibration	5.8 ± 6.11 (1.4, 10.15)	1.03	−1.47 ± 11.06 (−9.38, 6.44)	0.16	−1.8 ± 10.19 (−9.12, 5.46)	0.17
	Vibration-postvibration	29.98 ± 16.83 (17.94, 42.02)	2.16	24.96 ± 17.00 (12.79, 37.12)	1.78	−4.55 ± 7.52 (−9.94, 0.82)	0.53

Abbreviations: BOSU, Both Sides Up Balance Trainer (Hedstrom Fitness, Ashland, OH); CI, confidence interval; ES, Hedges *g* effect size; HEALTHY, healthy young adults.

vibration (the interaction of Pre to Vibration was approaching significance [$P = .06$], whereas the interaction of Vibration to Post was highly significant [$P < .001$]), but the overall behavior was similar between groups. Changes in excursion in response to vibration on each surface per group, accompanied by their 95% confidence intervals, and the respective effect sizes are displayed in Table 1. Response patterns between groups across surfaces can be seen in Figure 2.

Response to Vibration: Complexity Index

The variances were homogeneous, as assessed by the Levene test for equality of variances ($P > .05$). Because the Mauchly test of sphericity was significant, a Greenhouse-Geisser correction was applied. As shown in Figure 3A, for HEALTHY, we found a significant interaction of Pre to Vibration ($P < .001$). The pattern Vibration to Post was similar among surfaces, with a main effect of surface ($P < .001$) and vibration ($P < .001$). For CAI (Figure 3B), the interaction of Pre to Vibration was not significant, possibly because of larger variation within the group, and there was a significant main effect of surface ($P < .001$) but not vibration ($P = .13$). Similar to HEALTHY, the interaction of Vibration to Post was not significant, with a significant main effect of surface ($P < .001$) and vibration ($P = .009$). Complexity-index changes in response to vibration by surface and group, including the respective effect-size estimates, are presented in Table 2. Given the small sample of the CAI group, we urge the reader to view the Tables and Figures to appreciate the overall similar patterns between groups.

Shuffled Data

A visual display of SampEn across scale factors and complexity patterns in response to vibration across surfaces and between groups is provided in Figure 3C and D. Also represented in these figures are the results when data points were randomly shuffled (light gray lines). The shuffled data displayed in Figure 3 (left side) displayed complexity values that were more than twice as high as those from the actual data but showed similar values on all surfaces for both participant groups. A decreasing pattern across scales, unlike the increasing pattern observed for the actual data, for HEALTHY and CAI is also illustrated in Figure 3C and D. This is typical of white noise[22] and would be expected from shuffled data. All paired *t* tests at each scale factor were different at $P < .001$ (t statistic ranged from 28.15 to 72.34 for HEALTHY and from 14.06 to 102.01 for CAI), indicating that our data were not derived from a random source.

DISCUSSION

The primary purpose of our study was to examine the typical response to vibration given different support surfaces based on a traditional, well-established measure of postural control (ie, postural-sway excursion).[44] In addition, the recent postural-control literature highlights the importance of variability and complexity of the postural-sway signal and calls for quantifications of the structure of the COP signal to complement the traditional analysis of postural steadiness.[44] We therefore also explored the utility of MSE, a novel measure of postural-sway complexity.[23] As hypothesized, we observed vibration-induced falling when young adults were standing on the floor, whereas the excursion response to vibration, as indicated by a dramatic decrease in the effect size between floor and foam to BOSU, decreased as the challenge induced by the compliant surface increased. In fact, when standing on the BOSU, participants reduced their excursion response, such that it was reversed (ie, excursion was lower with and after vibration, as compared with before vibration). Changes in the complexity index in response to vibration were enhanced on the foam and BOSU as compared with the floor. Lastly, the pattern of responses was similar between groups.

Proprioceptive exercises are widely used for balance rehabilitation of athletes after ankle sprains[3–5] and for prevention of sport injuries (typically combined with other activities).[45] They have also been shown to reduce postural sway in healthy adults,[46] but their specific effect on proprioception has been questioned.[8,47] Previous motor-control investigators[13,40] adopted a vibration-induced–falling paradigm to investigate the rationale on unstable-surfaces training. They showed a reduced response on a sway-referenced platform or foam pad[15] compared with a rigid surface. It was suggested that the effect of confusing proprioceptive input generated by vibration was reduced because of a decrease in the integration of ankle proprioception cues.[13] We expand on these findings by demonstrating a decrease in the falling response to vibration on a particularly challenging compliant surface (a BOSU ball), comparing changes with and after vibration. In a companion paper,[33] we also reported increased visual dependence during stance on the BOSU as compared with the foam and floor conditions. Taken together and supported by others,[13,40] these findings suggest that

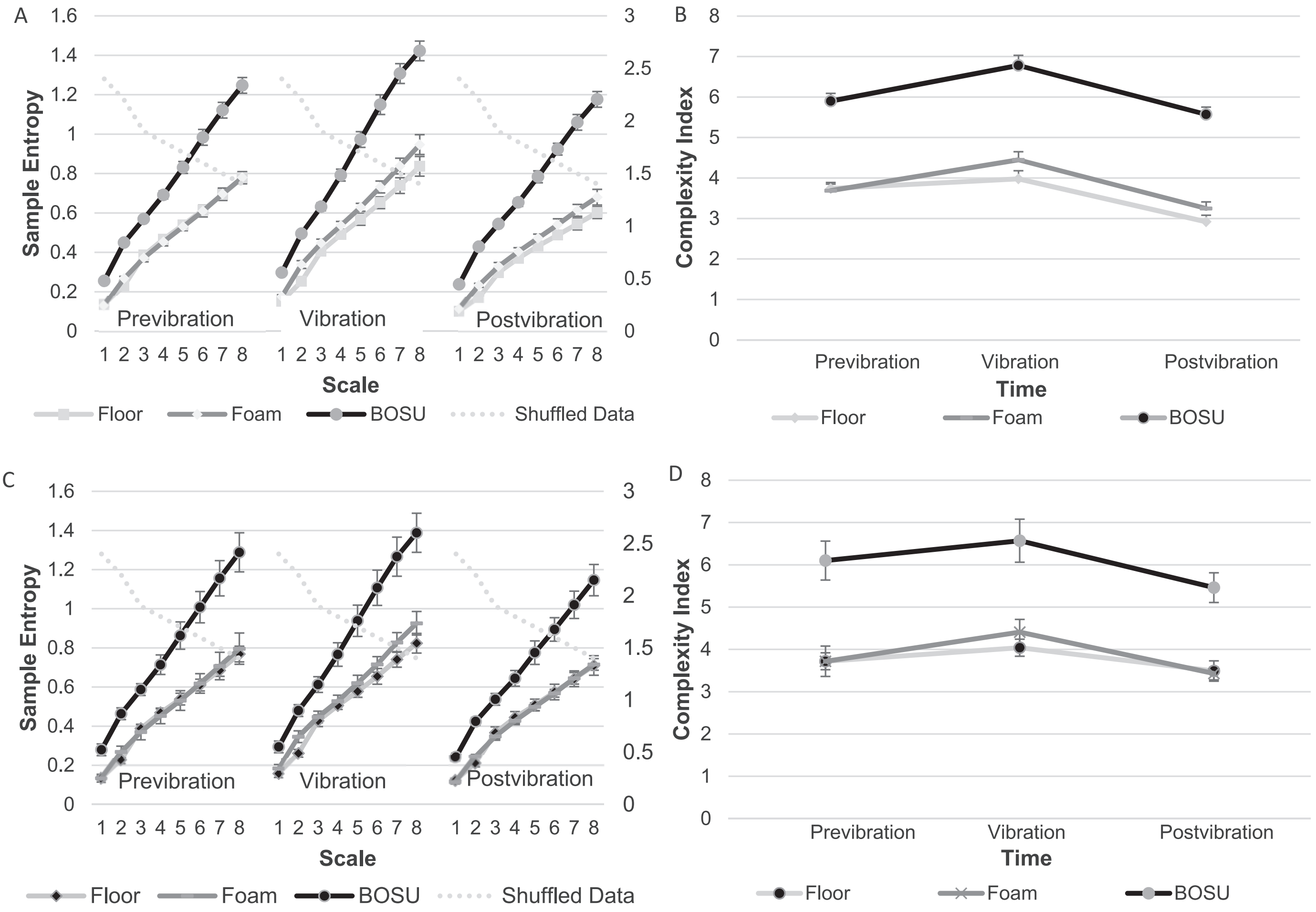

Figure 3. Sample entropy in the anterior-posterior direction as a function of scale factor and 3 time periods (previbration, vibration, and postvibration) across surfaces for A, healthy young adults and C, adults with chronic ankle instability (CAI). Error bars represent standard error of the mean. Note higher complexity on the Both Sides Up Balance Trainer (BOSU; Hedstrom Fitness, Ashland, OH) with no difference between the floor and foam (overlapping lines) previbration. Increased complexity with vibration is greater on the BOSU and foam compared with the floor. Decreased complexity postvibration is similar on all 3 surfaces. The light gray line represents the results when the data points were randomly shuffled. Shuffled values were about twice as high and are therefore presented on a secondary axis (right vertical axis). The area under the sample entropy curve is expressed as the complexity index. The complexity index in the anterior-posterior plane (vertical axis) is presented as a function of time (previbration, vibration, and postvibration) across surfaces for the B, healthy, and D, CAI groups. Error bars represent standard error of the mean and indicate that the variation was larger in the CAI group.

proprioceptive integration for postural control is reduced, and certainly not increased, during stance on challenging compliant surfaces. Thus, if the clinical purpose is to specifically facilitate ankle proprioception, different strategies might need to be developed and the term *proprioceptive training* as it applies to lower leg rehabilitation should be reconsidered.

The observed response to vibration when participants were standing on the BOSU was particularly surprising to us. Although we expected a reduction in excursion compared with the floor, we did not expect that excursion postvibration would be lower than previbration. Incidentally, participants in both groups gave unsolicited comments that the vibration made it easier for them to balance on the BOSU ball. Thus, it is possible that vibration, which is known to create proprioceptive confusion when young adults are standing on a stable support,[16,18] may become useful proprioceptive information and facilitate cocontraction during stance on continuously changing compliant surfaces such as BOSU balls. Vibration also led to increased complexity on the more-challenging surfaces. It is therefore possible that tendon vibration could be considered a specific rehabilitation modality. An example of a similar intervention that has been used before is stochastic-resonance stimulation. Balance exercises combined with electrical stochastic-resonance stimulation have led to improved outcomes in patients with CAI compared with those who performed the exercises alone.[48] It has been suggested that stochastic-resonance enhances the sensitivity of proprioceptive input and central nervous system output.[49] If local vibrating devices operate in a similar fashion, they could be used in balance rehabilitation. This should be explored in future clinical research.

Multiscale entropy has been reported in several studies[25,26] as a sensitive measure of postural control in people with neurologic conditions or balance deficits. However, MSE has not been extensively studied in healthy, active, young adults. Our results show clear differences between those measurement paradigms; this calls for future research on MSE in healthy, active populations. Overall, complexity levels, as measured by MSE and the derived complexity index, were much higher during stance on the BOSU for

Table 2. Changes in Complexity Index by Surface and Group Over 2 Time Points: Previbration to Vibration and Vibration to Postvibration

		Surface					
		Floor		Foam		BOSU	
Group	Time	Mean ± SD (95% CI)	ES	Mean ± SD (95% CI)	ES	Mean ± SD (95% CI)	ES
HEALTHY	Previbration-vibration	0.24 ± 0.75 (−0.04, 0.52)	0.24	0.77 ± 0.71 (0.5, 1.03)	0.78	0.88 ± 0.85 (0.56, 1.2)	0.72
	Vibration-postvibration	−1.06 ± 0.82 (−1.36, −0.75)	1.07	−1.2 ± 0.64 (−1.4, −0.96)	1.21	−1.2 ± 0.68 (−1.46, −0.96)	1
Chronic ankle instability	Previbration-vibration	0.32 ± 0.82 (−0.26, 0.9)	0.44	0.69 ± 1.38 (−0.3, 1.67)	0.64	0.48 ± 0.63 (0.02, 0.93)	0.3
	Vibration-postvibration	−0.55 ± 0.91 (−1.2, 0.1)	0.69	−0.98 ± 0.97 (−1.7, −0.28)	1.26	−1.12 ± 0.93 (−1.78, −0.45)	0.74

Abbreviations: BOSU, Both Sides Up Balance Trainer (Hedstrom Fitness, Ashland, OH); CI, confidence interval; ES, Hedges *g* effect size; HEALTHY, healthy young adults.

both groups as compared with other surfaces. We also saw an increase in complexity index with vibration, which was similar between foam and BOSU, but was higher than on the floor, followed by a similar postvibration decrease on all surfaces. Some of these findings agree with previous work[24] showing that MSE is task dependent and increases when perturbations to postural control are introduced to healthy older adults. However, Busa et al[25] found that introducing challenge to patients with multiple sclerosis led to decreased complexity. This example shows that MSE may function differently in healthy young adults. Complexity may be reduced with disease and proprioceptive deficits,[26] yet MSE is a relatively new measure and, as such, specific values of "too little" or "too much" have not been clearly defined.[50] It is possible that the increased complexity during stance on challenging compliant surfaces in both groups could elucidate an underlying mechanism to other benefits of such exercises; however, more research is needed. Others suggested that variability that is too high (reflected in high complexity values) could in fact indicate decreased movement efficiency.[22] Because the decrease in complexity postvibration was greater on the BOSU and foam compared with the floor, one could argue that the vibration stimulus might have helped to regulate the system in a challenging environment. This warrants future investigation.

Limitations

A few limitations of this study should be noted. The pattern of vibration effects on postural control among surfaces did not differ between groups. The fact that the CAI sample was small and heterogeneous could explain the lack of significant differences. Although our inclusion criteria for the clinical group met the broad categories of the recommendations made by the International Ankle Consortium,[51] they do not cover all the specific guidelines, as this research was conducted before the publication of these guidelines. It is therefore possible that a sample with more-stringent criteria defining CAI will respond somewhat differently. In addition, the task we chose was bipedal stance, which might not have created an adequate challenge for young adults with unilateral ankle instability and could have allowed them to compensate using their less-impaired foot. Note that all the participants in this group reported spraining both ankles in the past but had 1 side they defined as worse. Our study focused on the well-reported anterior-posterior vibration-induced falling. As the interaction between tendon vibration and postural control in people with CAI is further explored, we propose that lateral stimulation (rather than posterior), for example of the fibularis longus tendon, could potentially target more directly the area and plane of motion of the affected ankle and would perhaps be more useful in this population.

In addition to the clinical sample's being small and diverse, the CAI group was significantly younger. We believe this did not affect the results, as there were no significant differences between groups regardless of age, and we sampled from a narrow age range (18–40). Because we aimed to test the interaction between challenging environmental conditions and vibration among a sample of people who were healthy and fit, we asked participants to stand with their feet together on the floor and on the foam. This position was not feasible on the BOSU. It is possible that the different stance position could partially explain the decreased excursion response to vibration on the BOSU. Nevertheless, our findings are consistent with previous results showing a reduced effect of vibration on the unstable support. In addition, the complexity-index response to vibration was almost identical on the foam and the BOSU despite the different stance positions. Limiting participants' peripheral vision is not typically done in the clinic or sports field. Although this might have increased the level of difficulty of the tasks, any effect would be similar among the surfaces tested within this study. A concern that higher complexity on the compliant surfaces could be confounded by the various heights of the surfaces and their distance from the force platform was refuted when we explored the correlation coefficients between height and complexity index and found them to generally approximate 0. Finally, the test-retest (between-sessions) reliability of the excursion measure has been reported only in older adults, whereas that of MSE has not been reported before and should be investigated in future research.

Clinical Implications

When a single training session is conducted with a young adult for the purpose of improving proprioceptive function, practicing static stance on a highly challenging compliant surface may not be the right choice. Our work showed a decreased response to proprioceptive cues within this study, based on a traditional, commonly used measure of postural steadiness, and an enhanced response to visual cues[33] when young adults were standing on a BOSU ball compared with the floor (stable surface) or foam (less-challenging compliant surface). This might suggest, though not directly tested in our research, that long-term changes in balance performance after static balance training on BOSU balls relate to underlying increased visual dependence rather than improved proprioceptive function. Based on our findings and mounting evidence from sports and neurosciences and according to the sensory weighting theory, we propose that training under less-challenging surface conditions and more-challenging visual conditions (eg, eyes closed or dynamic visual environments) may better facilitate the use of somatosensory information. Accordingly, we cautiously propose that the term *proprioceptive training* as it refers to static balance exercises on unstable surfaces should be reconsidered. These results should be taken with caution because the clinical sample in this study was small and diverse, and, as in any research, alternative explanations should be considered. In our paradigm, it is possible that standing on the BOSU was challenging to the degree that the addition of vibration forced participants to freeze their degrees of freedom and reduce their sway. Indeed, postural-sway complexity was very much increased on the BOSU before and during vibration but reduced after tendon vibration. In addition, this was a single-session laboratory study and any suggestions regarding potential intervention effects should be tested in longitudinal training studies.

CONCLUSIONS

Participants' maximal COP displacement in response to a brief Achilles tendon vibration when standing on foam was attenuated as compared with stance on the floor. The COP displacement in response to the brief Achilles tendon vibration decreased when participants stood on the BOSU. Changes in complexity index during and after vibration were enhanced on the more-challenging surfaces of foam and BOSU. This might suggest that people attend less to proprioceptive cues from their lower legs when balancing on challenging compliant surfaces compared with standing on a stable surface. Further analysis of direct proprioceptive activation through H-reflex changes during stance on challenging surfaces may elucidate underlying mechanisms of this intervention technique. As the underlying sensory mechanism of different balance interventions continues to be explored, the usefulness of brief tendon vibration should be investigated. Future researchers should also investigate the utility of MSE with regard to sport-related injuries, as the traditional and nonlinear measures reflect different aspects of postural control.

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