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ORIGINAL ARTICLE

Effects of tibialis anterior vibration on postural control when exposed to support surface translations

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ABSTRACT
The sensory re-weighting theory suggests unreliable inputs may be down-weighted to favor more reliable sensory information and thus maintain proper postural control. This study investigated the effects of tibialis anterior (TA) vibration on center of pressure (COP) motion in healthy individuals exposed to support surface translations to further explore the concept of sensory re-weighting. Twenty healthy young adults stood with eyes closed and arms across their chest while exposed to randomized blocks of five trials. Each trial lasted 8 s, with TA vibration either on or off. After 2 s, a sudden backward or forward translation occurred. Anterior–posterior (A/P) COP data were evaluated during the preparatory (first 2 s), perturbation (next 3 s), and recovery (last 3 s) phases to assess the effect of vibration on perturbation response features. The knowledge of an impending perturbation resulted in reduced anterior COP motion with TA vibration in the preparatory phase relative to the magnitude of anterior motion typically observed during TA vibration. During the perturbation phase, vibration did not influence COP motion. However, during the recovery phase vibration induced greater anterior COP motion than during trials without vibration. The fact that TA vibration produced differing effects on COP motion depending upon the phase of the perturbation response may suggest that the immediate context during which postural control is being regulated affects A/P COP responses to TA vibration. This indicates that proprioceptive information is likely continuously re-weighted according to the context in order to maintain effective postural control.

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Vibration; proprioception; balance; posture; center of pressure; perturbation

Introduction

To remain upright during quiet stance, the projection of a person's center of gravity (COG) must remain within the area of their base of support (Massion 1984; Slijper and Latash 2004). Maintaining balance requires the central nervous system (CNS) to integrate several sensory inputs from visual, vestibular, and somatosensory sources to make appropriate postural adjustments via both closed- and open-loop processes (Nashner 1977; Massion 1984; Priplata et al. 2002; Smiley-Oyen et al. 2002; Horak 2006; Lee et al. 2012b; Dettmer et al. 2013). The sensory inputs contribute to the immediate (moment-to-moment) context in which a person's postural control is being regulated. It has been suggested that the CNS has the ability to ignore inaccurate or irrelevant stimuli from certain sensory systems in favor of relying on more accurate information from other sensory systems via a process known as sensory re-weighting. This proposed mechanism may increase or decrease the influence of specific sensory inputs enabling more effective postural control (Carver et al. 2006; Dettmer et al. 2013; Volkening et al. 2014).

Numerous studies have reported the ability of vibration to modify sensory input by preferentially activating primary afferent fibers (Type Ia) (Slijper and Latash 2004; MacDonell et al. 2010; Thompson et al. 2011; Duclos et al. 2014). Such vibration generates proprioceptive misinformation on the vibrated muscles' lengths, resulting in them being perceived as longer than they actually are (Lackner and Levine 1979; Lackner et al. 2000; Ceyte et al. 2007; Dettmer et al. 2013). Vibration of the calf muscles or Achilles tendons tends to produce backward postural sways (Ivanenko et al. 1999; Ceyte et al. 2007; Caudron et al. 2010a, 2010b; Duclos et al. 2014), while vibration of the tibialis anterior (TA) muscles or tendons tends to elicit a forward postural sway (Michel-Pellegrino et al. 2006; Caudron et al. 2010a; Temple et al. 2014). Center of pressure (COP) data obtained from force plates is often used to observe such postural changes (Caudron et al. 2010a; Duclos et al. 2014). The presence of these vibration-induced postural responses appears to be context specific, with multiple factors potentially impacting the body's response to vibration and likely the weighting of importance placed on proprioceptive afferents (Ivanenko et al. 2000; Vuillerme et al. 2002; Dettmer et al. 2013).

It is well known that the presence of visual feedback can negate or reduce either the behavioral consequences of muscle vibration, for example, postural sway, or the illusions often associated with vibration (Vuillerme and Cuisinier 2008; Bove et al. 2009; Gomez et al. 2009). These findings suggest that proprioceptive input is immediately down-weighted in favor of visual input (Vuillerme and Cuisinier 2008; Gomez

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et al. 2009). Likewise, in the absence of vision, the presence of light touch has also been shown to alter postural responses to tendon and muscle vibration such that contributions from sensory input are likely re-weighted in order to best control and stabilize balance (Ivanenko et al. 1999; Lackner et al. 2000; Vuillerme and Cuisinier 2008). These findings further support the importance of context in a person's response to vibration with the situation, movement, associated postural control goals, and types of sensory input available substantially impacting the postural response to lower limb tendon vibration.

Hatzitaki et al. (2004) found that Achilles tendon vibration induced significant posterior sway when combined with a toes-down perturbation. In this scenario, the toes-down perturbation and vibration would generate directional sways that counteract one another. Interestingly though, Achilles tendon vibration did not induce significantly more backward sway when it was combined with a toes-up perturbation, in which both the vibration and perturbation would generate backward sway and potentially further threaten postural stability. The authors concluded that the CNS must have the ability to quickly determine if a stimulus like vibration is beneficial or threatening to stability and either utilize it or down-weight it accordingly (Hatzitaki et al. 2004).

Study aim

To further explore the concept that a specific sensory input can be re-weighted depending upon the movement context, the current study used a protocol similar to that of Hatzitaki et al., but used horizontal translational perturbations and TA vibration instead of the toes-up/down perturbations and Achilles tendon vibration. The current protocol provided the opportunity to determine if typical responses to ankle musculature vibration during bipedal stance were maintained during support surface perturbations or if the perturbations modified the typical vibration response, thereby suggesting that context plays a major role in the weighting of sensory input.

Materials and methods

Subjects

Twenty young healthy adults (15 males, 5 females, mean age =25.8 ± 3.9) participated in this study. All subjects were required to fill out a physical activity readiness questionnaire (PAR-Q) prior to the study session. Individuals were excluded if they had any known neurological dysfunction, heart conditions, blood pressure irregularities, breathing difficulties, bone or joint issues, were pregnant, had diabetes, were epileptic, had balance problems, or had any major surgeries recently that might impact their balance. In addition, subjects over the age of 35 were also excluded to rule out the potential for age-related changes in somatosensation affecting results. Informed consent was obtained from each subject prior to the start of the experimental procedures. Approval to conduct this study was granted by the Committees for the Protection of Human Subjects at the University of Houston, which conforms to the Declaration of Helsinki.

Procedure

Bipedal standing subjects were exposed to randomized blocks of either a single backward or forward horizontal perturbation with or without the application of TA vibration (on or off). Perturbations were applied with the use of a computer-controlled, hydraulically driven force plate platform system (Equitest; NeuroCom International, Clackamas, OR, USA), at an amplitude of 6.35 cm and lasted for 0.4 s. Each testing block consisted of five consecutive, 8-s trials of the same perturbation condition (i.e., same direction translation and vibration situation). Vibration was applied bilaterally to the TA muscles using portable vibrators held against the muscle bellies with rubber straps (VB115; Techno-Concept, Cereste, France) for the entire duration of each trial that included vibration. The vibration frequency was set at 80 Hz during all conditions with TA vibration to preferentially activate muscle spindles and thereby elicit a postural response (Michel-Pellegrino et al. 2006; Thompson et al. 2007). On trials that included vibration, the vibrators were activated at the start of the trial and remained active for the duration of the trial.

During the testing protocol, subjects were positioned barefoot on the NeuroCom platform with feet spaced apart at a width dependent upon the subject's height, compliant with the instructions for use (Balance Manager® Systems 2008). Prior to all trials, they were instructed to close their eyes, hold their arms across their chest, and stand as upright as possible. The subjects were aware they would be experiencing a translational perturbation; however, perturbation direction and vibration condition were never explicitly stated to the subject, regardless of vibration condition.

Data analysis

The A/P COP data obtained from the force plate system and sampled at 100 Hz were utilized in calculating all dependent variables defined in this study. Processing of COP signals was performed using MATLAB (The Math Works, Natick, MA, USA). A/P COP motion from each trial was low-pass filtered with a zero phase, second-order Butterworth filter with a 10-Hz cutoff frequency, and demeaned to a zero point based upon the first data point collected as has been done in previous research (Duclos et al. 2014). The cutoff frequency was determined by the fact that the frequency bandwidth of body kinematics is below 10 Hz during quiet standing (Winter 1995; Sienko et al. 2010; Lee et al. 2013). All dependent variables defined herein were calculated using the A/P COP waveforms, as the predominant motion response to the perturbations occurring within the sagittal plane.

To assess the preparation to the impending perturbation in terms of COP motion, the support surface perturbation always occurred 2 s after the initiation of the trial. Each trial was divided into three distinct temporal segments. The first segment was defined as a *preparatory phase* and consisted of the first 2 s of data beginning with the initiation of the trial to the perturbation onset. The next segment was defined as a *perturbation phase*, consisting of the next 3 s of data beginning from the perturbation onset. The *recovery phase* was comprised of the last 3 s of data from the trial, during which

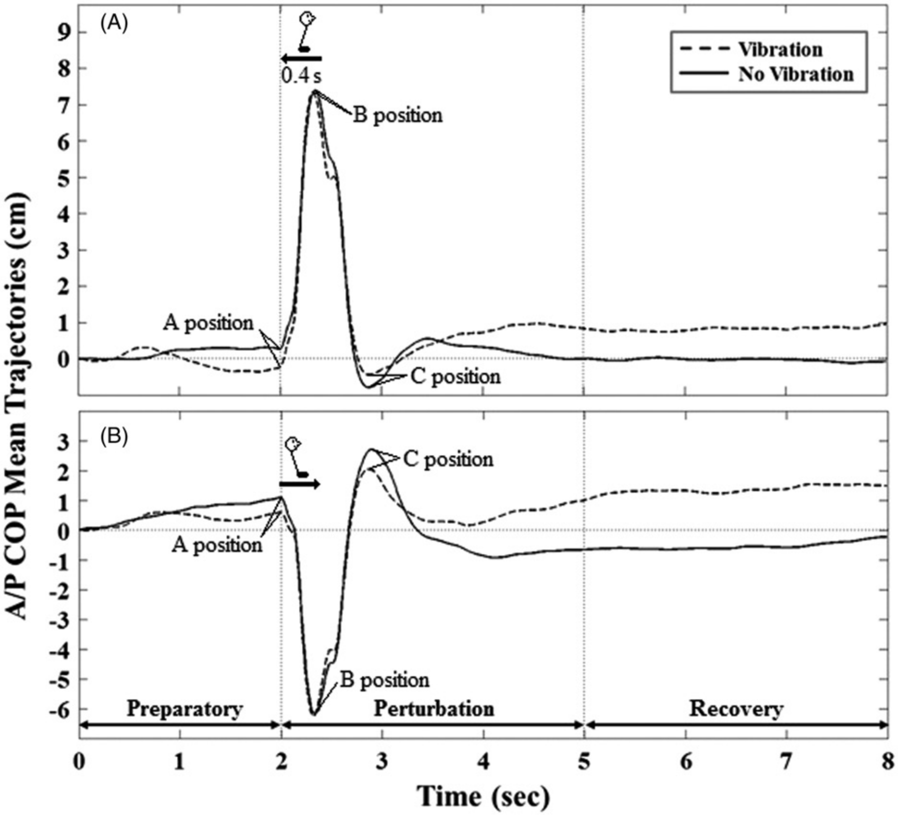

Figure 1. A/P COP mean trajectories for all subjects when exposed to (A) backward and (B) forward perturbations. Vertical dotted lines separate the three temporal phases: preparatory (0–2 s), perturbation (2–5 s), and recovery (5–8 s). Dashed lines indicate the mean trajectories for subjects while exposed to TA vibration, and solid lines display the mean trajectories without vibration. Corresponding A, B, and C positions are marked for each mean trajectory. Positive values indicate trajectories more anterior than when trials started, while negative values indicate trajectories more posterior than when the trials began.

the A/P COP motion stabilized. Various dependent measures were calculated from the data obtained during each of these segments.

For the following variables, mean values were calculated from the data obtained from each trial and specific analysis phase: COP position, root mean square (RMS), velocity, and mean power frequency (MPF). A/P COP mean position indicated how far subjects shifted their relative A/P COP position in response to the vibration stimulus. The response to the perturbation that was reflected in the perturbation phase includes both large anterior and posterior COP shift components and therefore a mean value during this phase does not accurately portray the magnitude of responses in a certain direction (Figure 1). Thus, A/P COP motion and RMS during the perturbation phase was not included in the analyses. RMS was computed as the square root of the time average of the squared A/P COP motion. This measure provides information about the amplitude of the COP motion as well as the variability in the A/P direction, and was used as a means of further describing the sway properties in response to TA vibration during the preparatory and recovery phases.

Three specific points were utilized to characterize motion of the A/P COP during the perturbation phase. The first obtained point was labeled the A position and was defined as the subject's A/P COP mean trajectory position when the perturbation was initiated. The first peak response in the A/P COP mean trajectory after perturbation onset was labeled the B position. This point corresponded to the maximum A/P COP mean trajectory position for backward perturbations or the minimum A/P COP mean trajectory position for forward perturbations. The B position provided a measure of a subject's maximum displacement to the perturbation on their A/P COP mean trajectories. The C position was then identified as the second peak response in the A/P COP mean trajectory after the perturbation, and was a measure of the peak COP position achieved by a subject in responding to the perturbation with an automatic postural adjustment. For all COP variables, positive values depict anterior COP shifts, while negative values indicated posterior COP shifts from when the trials began.

Shapiro–Wilk's test of normality and evaluation of Q-Q plots indicated the data were normally distributed. A Levene's test of equality of error variances revealed all outcome measures displayed homogeneity of variance. In order to determine if there was an adaptation effect across the five trials conducted for each condition, a repeated measures analysis of variance (ANOVA) was conducted looking at the possible effects of perturbation direction (forward or backward), phase (preparatory, perturbation, or recovery), vibration (on or off), and trial number (1–5) on the A/P COP mean position. Two-way multivariate analyses of variance (MANOVAs) were then used to test for main effects of perturbation direction and vibration, as well as interactions. Hypotheses for the main effects of direction and vibration were tested using an *F*-test. *Post hoc* analyses for all measures in the MANOVAs were performed using Sidak's method. The level of significance was set to $p < 0.05$.

Results

Adaptation effects

The repeated measures ANOVA revealed no effect of trials on the A/P COP position measures, indicating there was no adaptation associated with multiple trials [$F(4, 76) = 1.38$, $p = 0.25$]. An illustration of the lack of adaption of the A/P COP position is provided (Figure 2). Therefore, the five consecutive repetitions in a block of each experimental condition were averaged for each subject in all measures herein calculated (mean position, RMS, A position, B position, C position, mean velocity, and MPF).

Vibration effects

Several significant effects of vibration were found in variables measured during the different phases. Following the finding of a significant main effect of vibration on the A position [$F(1, 76) = 8.74$, $p = 0.004$], *post hoc* analysis indicated the A position was significantly less anterior with vibration than without for both backward [$F(1, 76) = 4.59$, $p = 0.035$] and forward [$F(1, 76) = 4.16$, $p = 0.045$] perturbations (Figure 1). Anticipatory postural adjustments associated with the preparation for the impending external perturbation are therefore influenced by vibration. Likewise, a significant main effect of vibration during the preparatory phase [$F(1, 76) = 5.46$, $p = 0.022$] revealed that mean position was also less anterior for vibration trials than trials without vibration (Figure 1). However, *post hoc* analyses for mean position *between* vibration conditions were not significant in the preparatory phase (Figure 3). There were no main effects of vibration for RMS, mean velocity, or MPF in the preparatory phase, as well as no differences in the B position, C position, mean velocity, or MPF during the perturbation phase. There was a significant main effect of vibration for the mean position during the recovery phase [$F(1, 76) = 32.31$, $p < 0.001$]. Mean position was more anterior with vibration than without vibration, which is opposite to the effect of vibration observed in the preparatory phase. *Post hoc* analyses revealed significantly more anterior mean positions with vibration than without vibration for both the backward [$F(1, 76) = 6.19$, $p = 0.015$] and forward [$F(1, 76) = 30.81$, $p < 0.001$] perturbations (Figure 3). There was a significant main effect of vibration on mean velocity during recovery with greater velocities with vibration than without [$F(1, 76) = 15.46$, $p < 0.001$]. *Post hoc* analysis revealed increased velocity with vibration in both the backward [$F(1, 76) = 6.27$, $p = 0.014$] and forward [$F(1, 76) = 9.34$, $p = 0.003$] perturbation directions. Vibration also resulted in a significantly greater level of RMS [$F(1, 76) = 6.72$, $p = 0.011$] during the recovery phase. *Post hoc* analyses indicated that RMS was significantly greater for the forward perturbations [$F(1, 76) = 6.31$, $p = 0.014$] with vibration than without during the recovery

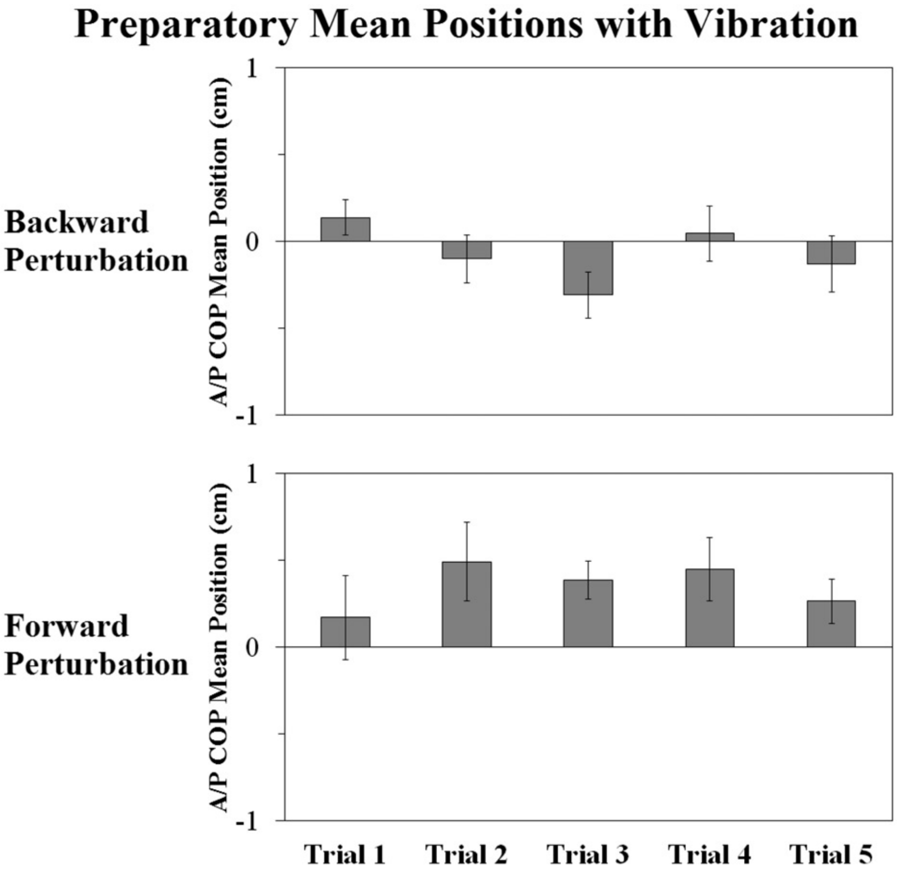

Figure 2. Bar graphs depicting the A/P COP mean positions ±1 standard error for the five consecutive trials during the preparatory period for trials with vibration. A repeated measures ANOVA indicated no significant effects of trial [$F(4, 76) = 1.38$, $p = 0.25$]; therefore, no adaptation to the repeated perturbations was observed. Since no adaptation across the trials was noted, mean data of the five consecutives trials was utilized in the two-way MANOVAs to compare vibration and vibration × direction interaction effects.

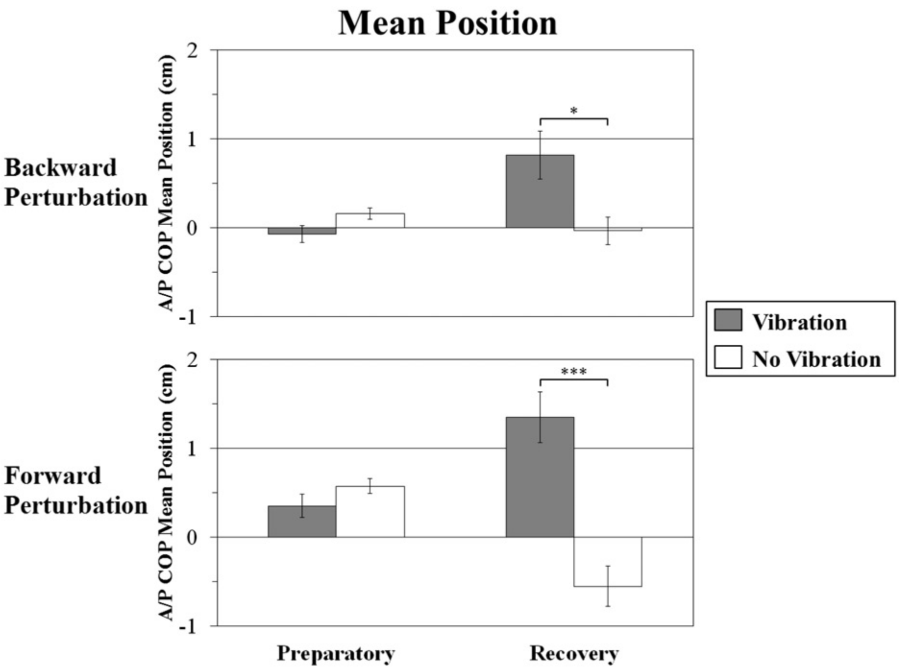

Figure 3. Bar graphs depicting the means for the A/P COP mean position ±1 standard error during the preparatory and recovery phases for the backward and forward translating perturbations. Means of trials with TA vibration are depicted using grey shaded bars, while the white bars indicate means of trials without TA vibration. Positive values indicate mean positions more anterior than when trials started, while negative values indicate mean positions more posterior than when the trials began. Horizontal comparison lines depict significant differences between vibration conditions. Asterisks denote the level of statistical significance: $^{*}p < 0.05$ and $^{***}p < 0.001$.

phase. Consistent with the findings in the preparatory and perturbation phases, there was no significant effect of vibration on MPF in the recovery phase, thus vibration did not impact the frequency characteristics of the A/P COP motion during any phase.

Vibration × direction interaction effects

One significant interaction effect of vibration and perturbation direction was found for mean position during the recovery phase [$F(1, 76) = 4.69$, $p = 0.034$]. The differences in the A/P COP motion between the vibration and no vibration conditions are greater in forward perturbation condition than those in the backward perturbation condition (Figures 1 and 3). Effects of vibration on A/P COP varied according to the specific phase of the trials, with COP trajectories being less anterior with vibration relative to no vibration in the preparatory phase, having no effect during the perturbation phase, and resulting in more anterior trajectories during the recovery phase (Figure 1).

Discussion

This study explored the effects of bilateral TA muscle vibration on postural control when applied before, during, and after translational perturbations of support surfaces during bipedal stance. Time and frequency domain properties of kinetic measures were examined by the mean position, RMS, peak responses, mean velocity, and MPF of the A/P COP. Differential effects of TA vibration were observed dependent on the response phase of a perturbation trial, thereby suggesting that the immediate context in which postural control is being regulated is accounted for.

The results from the preparatory phase of the perturbation trials reveal a main effect of vibration on the mean position of the COP and the A position (Figures 1 and 3). Of particular interest is that the direction of COP shift in response to vibration during this preparatory phase is opposite to that observed with TA vibration during quiet bipedal stance (Michel-Pellegrino et al. 2006; Caudron et al. 2010a; Temple et al. 2014). Specifically, TA vibration during quiet stance results in anterior COP motion but in conditions that include a support surface translation as in this study, the vibration results in a posterior shift of the COP relative to that observed during quiet stance with TA vibration. These results suggest that the immediate context of the situation plays an important role in the control of the COP trajectory exhibited in response to TA muscle vibration. The expectation of a perturbation seems to be a salient point of context with the potential to produce a sway response to TA vibration that is atypical from that observed in the absence of an impending perturbation. The threat of an upcoming perturbation led to a re-weighting of ankle musculature proprioception in a manner deemed beneficial to preparing for the perturbation.

Additional support of the concept of context-specific responses to vibration is the finding that during the perturbation phase there is no effect of vibration on COP motion. There were no differences in the B and C positions of the COP trajectories with the addition of vibration. This finding again suggests that the movement context during which vibration is applied is important. In this situation, the proprioceptive input associated with vibration was down-weighted and effectively ignored during the immediate response to the perturbation which coincides with the time of greatest postural threat. The fact that vibration did not impact A/P peak COP motion observed during the perturbation phase in the present study appears to coincide with previous literature. As mentioned in the introduction, one study found ankle tendon vibration combined with toes-up perturbations did not significantly disrupt COP motion. In fact, when joined with toes-down perturbations the ankle vibration actually seemed to provide a stabilizing effect (Hatzitaki et al. 2004). Although our study did not find a beneficial impact of TA vibration on COP during a certain perturbation direction, we concur that the stimulus was not found to significantly hinder healthy subjects' response to perturbations or promote further instability. Indeed, down-weighting of proprioceptive information from vibrated muscles during bipedal posture has been suggested by others when combined with additional threats to postural stability such as perturbations (Hatzitaki et al. 2004), muscle fatigue (Vuillerme et al. 2002), or platform instability (Ivanenko et al. 1999, 2000; Dettmer et al. 2013). Our research coincides with these prior studies that proprioceptive inputs from vibrated muscles are likely down-weighted during the perturbation phase, when the threat to postural stability is the greatest. We agree that when balance is additionally challenged, the effects of vibration on postural control are minimized.

The COP during the recovery phase was shifted significantly more anteriorly during the trials with vibration compared to trials without, regardless of the direction of the preceding perturbation. This finding indicates that once the external perturbation has been responded to in a way that the threat to balance has been eliminated, the disrupting proprioception associated with TA vibration is responded to in the typical manner, that is, inducing forward COP motion. Collectively, the results indicate that different postural responses to TA vibration occur during the three phases associated with the perturbation trials, thereby providing support for the idea that proprioceptive input is being continually monitored and weighed by the postural control system depending upon the immediate contextual requirements for postural control. Others have similarly suggested that re-weighting occurs as a dynamic process rather than from a "fixed reference" and have observed postural effects when manipulating the sensory systems responsible for balance control (Peterka and Loughlin 2004; Hwang et al. 2014).

In conclusion, the current findings indicate that TA vibration can impose different A/P COP responses just prior to and immediately after exposure to backward and forward translating perturbations. The results reveal that the context in which postural control is operating can modify the response to a strong proprioceptive stimulus such as vibration. It is suggested that proprioceptive input supports adaptive coding of the body's spatial representation, and contributes to continuous sensory re-weighting, where the sensorimotor system is constantly regulating the contribution of multiple sources of sensory input to maintain equilibrium (Peterka and Loughlin 2004; Eikema et al. 2013; Hwang et al. 2014). To further understand the context in which vibration imposes postural changes on individuals, it is suggested that future research continue to evaluate postural responses to vibration applied to various body locations and characterize the responses with multiple kinetic as well as kinematic measures. Use of motion capture systems for kinematic analysis can allow for more precise analysis of postural strategies and contributions from different body segments to postural control when vibration is applied. Ultimately populations with certain neuromotor deficits should also be taken into account to better comprehend the implications for utilizing this simple sensory stimulus for therapeutic or training purposes to adjust for and correct posture. Finally, the aforementioned investigations will inform better design of sensory augmentation through vibrotactile biofeedback for balance disorders occurring from sensorimotor impairments, since vibrotactile biofeedback has been shown to improve postural control in individuals with vestibular dysfunction (Sienko et al. 2010; Wall and Kentala 2010; Lee et al. 2012a), older adults (Haggerty et al. 2012), and patients with Parkinson's disease (Nanhoe-Mahabier et al. 2012; Rossi-Izquierdo et al. 2013).

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Disclosure statement

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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