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Interaction of support surface stability and Achilles tendon vibration during a postural adaptation task

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ABSTRACT

Orchestration of sensory-motor information and adaptation to internal or external, acute or chronic changes is one of the fundamental features of human postural control. The postural control system is challenged on a daily basis, and displays a remarkable ability to adapt to both long and short term challenges. To explore the interaction between support surface stability and Achilles tendon vibration during a period of adaptation we used both a linear measure and a non-linear measure derived from center-of-pressure (COP) data. An equilibrium score (ES), based upon peak amplitude of anterior-posterior sway towards theoretical limits of stability was the linear measure used to assess postural performance. We observed early effects of vibration on postural stability, depending on support characteristics. Participants were able to decrease sway with extended practice over days, independent of support surface stability. Approximate entropy analysis of COP data provided additional information about control adaptation processes.

1. Introduction

Maintaining postural stability whether for standing, locomotion or other tasks, requires complex interactions between neuromotor processes, biomechanical constraints and the goals of the individual.

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The central nervous system (CNS) constantly processes information regarding position and torques provided by three primary sensory systems, the vestibular, visual and somatosensory (Horak, Nashner, & Diener, 1990; Lackner & DiZio, 2005). Information from these systems results in the detection of position and movement and the initiation of adequate muscular responses to maintain bipedal postural control.

It has been demonstrated that with practice, the CNS exhibits the ability to adapt to external perturbations and thereby to decrease postural sway (Fransson et al., 2003). This adaptive process is potentially due to several, distinct short- and longer term mechanisms of adaptation: one proposed mechanism is dynamic, sensory reweighting of available sensory information such that the CNS utilizes a weighted sum of available sensory information to maintain postural control. If one sensory channel provides unreliable information, it is downweighted in favor of more reliable channels (Carver, Kiemel, & Jeka, 2006; Haran & Keshner, 2008). Neurophysiological mechanisms underlying this theory are not yet fully understood, but several theories and models for sensory integration and reweighting have been presented (Maurer, Mergner, & Peterka, 2006, 2002, 2003; Peterka & Loughlin, 2004). A second element of adaptation involves the modification of postural strategies. This can include shifts towards a hip or ankle strategy, ‘‘leaning’’ and associated changes of biomechanical constraints, or general stiffening of lower leg joints and increased ankle musculature co-contraction (Almeida, Carvalho, & Talis, 2006; Benjuya, Melzer, & Kaplanski, 2004; Brumagne, Janssens, Knapen, Claeys, & Suuden-Johanson, 2008; Termoz et al., 2008). Additional adaptation has been proposed to be encompassed by a process labeled long-term consolidation, emerging from numerous repetitions of the task, representing an enduring motor learning effect that integrates the aforementioned features of adaptation for more efficient performance (Fransson, Johansson, Tjernström, & Magnusson, 2003; Tjernström, Bagher, Fransson, & Magnusson, 2010; Tjernström, Fransson, & Magnusson, 2005).

Given the important role of sensory contributions to action, researchers are often interested in challenging the postural control system by modifying specific input of various sensory channels. Muscle tendon vibration (most common at the Achilles tendon), is a technique that allows researchers to effectively challenge the postural control system by modifying sensory inputs primarily emerging from ankle muscle spindles in healthy or pathologic populations (Fransson, Johansson, Hafström, & Magnusson, 2000; Gurfinkel’, Kireeva, & Lebik, 1996; Roll et al., 1993; Thompson, Bélanger, & Fung, 2007, 2011). During vibration, Ia-afferents of the muscle spindles are preferentially stimulated (Ribot-Ciscar, Rossi-Durand, & Roll, 1998). This muscle spindle stimulation creates proprioceptive misinformation about the current muscle length and stretch (Matthews, 1986; Polónyová & Hlavacka, 2001), thereby generating sensations of muscle lengthening (Goodwin, McCloskey, & Matthews, 1972). A commonly described effect is a backwards leaning for compensation of the perceived (false) muscle lengthening and associated postural sway. This immediate effect on body orientation increases body sway and COP fluctuations (Barbieri et al., 2008; Ceyte et al., 2007; Lackner, 1988; Polónyová & Hlavacka, 2001; Roll, Vedel, & Roll, 1989; Thompson et al., 2007) especially when combined with occluded vision. Achilles tendon vibration creates a discrepancy between perceived afferent information from stretch receptors of the lower limb musculature, and other more reliable sources (vestibular system, joint or skin receptors, etc.), which ultimately affects postural stability.

The magnitude of influence of vibration on postural stability is highly context-dependent. For instance, postural sway in response to muscle tendon vibration while standing upright on an unstable support surface is reduced when compared to the vibration-induced sway while standing on a stable support surface (Ivanenko, Solopova, & Levik, 2000; Ivanenko, Talis, & Kazennikov, 1999). It has been suggested that if vibration is introduced while standing on an unstable support surface, the CNS is able to partially suppress or downweight proprioceptive sensory input that is of no or little informational value or is detrimental to postural stability (Hatzitaki, Pavlou, & Bronstein, 2004). However, the possible interaction between vibration and support stability could affect the time course of postural adaptation. Numerous investigations have combined different support surface characteristics, manipulating sensory conditions and investigating repetition of tasks to assess postural adaptation.

Linear analysis has traditionally dominated research and clinical assessments. However, analyses based on non-linear techniques are now more frequently being used to investigate postural control dynamics. Among the non-linear tools applied to postural control research is approximate entropy

(ApEn), a regularity statistic determining the predictability/regularity of variation in a time-series (Pincus, 1991; Pincus & Goldberger, 1994). ApEn has been shown to detect changes in motor control that might not be revealed by linear analysis, and results have been interpreted as potential modifications of motor control or biomechanical constraints (Cavanaugh et al., 2006). Recent data has highlighted the role of ApEn as a potentially useful supplementary analysis technique to traditional outcome measures of postural stability (Cavanaugh, Guskiewicz, & Stergiou, 2005; Cavanaugh, Mercer, & Stergiou, 2007; Dusing, Kyvelidou, Mercer, & Stergiou, 2009; Hong, Manor, & Li, 2007; Stergiou, 2004; Turnock & Layne, 2010).

The current study was designed to evaluate short- or longer term adaptation in response to different support surface characteristics and Achilles tendon vibration using both linear and non-linear measurements. It was hypothesized that initial application of vibration would increase COP motion, with more severe effects in the fixed-support condition; repeated practice with vibration would decrease COP motion in both support surface conditions, both in the short-term and in the longer term. Initial vibration would affect ApEn, but this effect would be influenced by support surface condition. Repeated practice with vibration would affect ApEn in both support surface conditions, both in the short-term and in the longer term.

2. Methods and materials

2.1. Subjects

The protocol was approved by the Committee for the Protection of Human Subjects (CPHS) at the University of Houston. Participants for the study were recruited from the University of Houston campus. Neuromuscular health was examined by having prospective participants fill out a Physical Activity Readiness Questionnaire and perform a partial Sensory Organization Test (SOT), in the respective condition they had been randomly assigned to (either 2 or 5). Exclusion criteria were reported potential neuromotor deficits or when the SOT showed an abnormal score. The cutoff score for exclusion was determined by normative data provided with the NeuroCom system (NeuroCom International, Clackamas, OR). For an age group of 20–59 years, the cutoff scores were 85 (SOT 2) and 52 (SOT 5). All recruited participants were included in the study. Eighteen ($n = 18$) young, healthy individuals between ages 18 to 35 (10 females; 8 males, mean age 24.1 ± 4.2 yrs; mean height 168.3 ± 10.8 cm; $M \pm SD$) participated in the study.

2.2. Design

All experimental sessions were conducted on the NeuroCom Balance Manager (NeuroCom International, Clackamas, OR) in the Center for Neuromotor and Biomechanics Research (CNBR). All participants were randomly assigned to one of two experimental conditions (condition 2 and 5) of the Sensory-Organization-Test (SOT). SOT 2 requires of participants to close their eyes and maintain upright stance on a fixed-support surface (FS). SOT 5 requires of participants to close their eyes and maintain upright stance while the support surface is unstable, and sway-referenced (SRS). In SOT 5, the surface rotates in anterior and posterior direction according to forces applied to the platform by the subject while trying to maintain quiet stance. This condition is designed to dampen proprioceptive signals, whereas muscle spindle information no longer provides reliable information about body verticality. This is combined with removal of visual reference, creating a challenging postural task. All testing was completed in stocking feet with arms crossed in front of the chest. During all test sessions, COP data were collected at 100 Hz.

Vibration was applied bilaterally on the Achilles tendons (see Fig. 1) at a frequency of 70 Hz (VB 115, Techno-Concept, Cereste, France). 70 Hz is within a range of frequencies shown to be effective in stimulating muscle spindles around the ankles (Polónyová & Hlavacka, 2001) and evoke postural responses.

Prior to the first session, informed consent and anthropometric data (age, gender and height) were obtained from each participant. Participants were familiarized with the sensation of muscle tendon

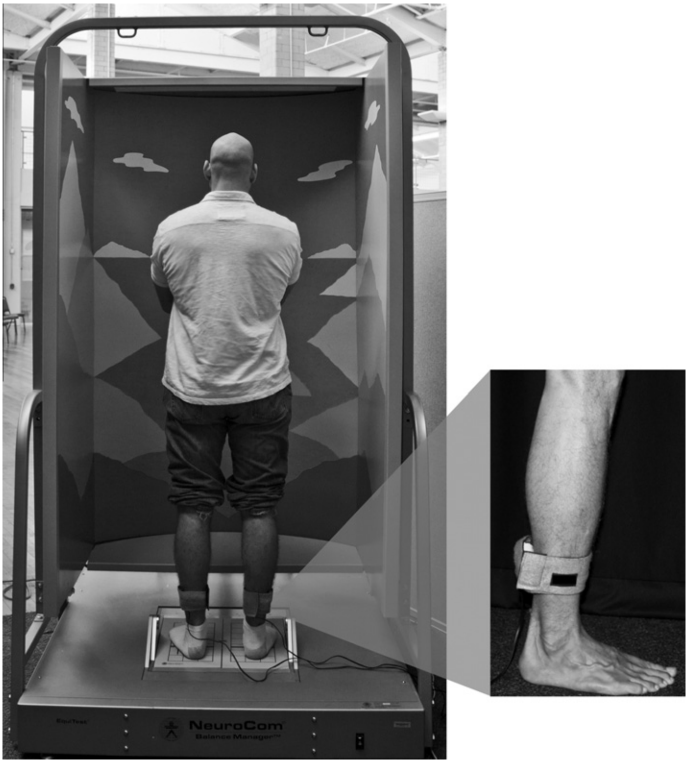

Fig. 1. Experimental setup for the current study. Force platform (NeuroCom Balance Manager) and Ia-afferent stimulation applied via local muscle tendon vibration (TechnoConcept VB 115).

vibration (while sitting in a chair) and performed three acclimatization trials of their assigned support condition. During these initial tests, the muscle vibrators were attached at the participants' ankles but were not activated. In the next session (following day), three trials of baseline data were collected (no vibration). Immediately after baseline testing, the first vibration test session was conducted. Each test session consisted of nine trials of 20 seconds each, with five-second breaks in between each single trial and a one minute rest period after every three trials. Participants were tested in their respective group support surface condition. An auditory stimulus signalled the start of the test. Vibration was always activated simultaneously with the start of a trial and was turned off between trials. Test sessions of nine trials per day were conducted for three consecutive days for all participants.

2.3. Data reduction

An equilibrium score (ES) for every single trial was obtained using EquiTest 8.0 software (NeuroCom International), which is based on estimated center-of-gravity variation obtained from anterior-posterior COP values. The center-of-gravity is estimated by using a second-order Butterworth digital filter (cut-off frequency of 0.85 Hz) on COP data in each time-series (Leitner et al., 2009). ES is expressed by the ratio of the peak-to-peak center-of-gravity (anterior-posterior direction, COGy) angular displacement to the theoretical maximum angular displacement limits of stability (approximately 12.5° in anterior-posterior direction). ES ranges between 0–100, whereas a score of 0 denotes a fall and 100 denotes perfect stability (NeuroCom, 1991). This method is the basis of computerized dynamic posturography (CDP) and has been used in a variety of clinical and scientific environments in order to make conclusions about postural stability of healthy subjects and patients (Roberts-Warrior et al., 2000; Yardley, Burgneay, Nazareth, & Luxon, 1998). Since this investigation aimed at assessing early effects, short- or longer term adaptation, we used different approaches for data reduction.

To answer the question of whether support surface condition affected response during the initial exposure to vibration, which was labelled as early effects, we compared the ES and ApEn baseline data with ES and ApEn data from the respective initial vibration trial. The methodology employed (i.e., data collection beginning simultaneously with vibration initiation) resulted in the well documented immediate backwards sway in response to vibration and subsequent drift back towards baseline being included in the calculation of both the ES and ApEn values. We were also interested in exploring the effects of support surface on the vibration response over a somewhat longer time period. To test for short and long term adaptation, the ES and ApEn data for each trial were centered relative to the respective baseline value for each subject, creating deviation scores to normalize for differences in the baseline means and variability between the fixed-support and sway-references support groups. For determination of short-term adaptation, we analyzed the centered data for trials 1–9 within each day. To assess longer term adaptation, we averaged the centered data from all nine trials in each day (day 1 through day 3) to compare between test days. Averaging of trials within days was justified by the fact that trial-to-trial trends in both conditions did not differ between testing days (i.e., no significant day-by-trial interaction. Since one of the goals of the experiment was to determine whether participants in their respective test condition would be able to fully adapt to the vibration perturbation, we determined the task as ‘‘learned’’ (vibration effects fully compensated) when participants had ES within one standard deviation of their initial baseline testing mean.

ApEn measures were calculated using a customized MatLab R2008a (Mathworks, Natick, MA) code and anterior-posterior COP-displacement data for each 20-s trial of the experiment (2000 data points per trial). According to data processing protocols established in former studies, the following settings were applied for MatLab analysis: A series length of 2 ($m = 2$ data points), an error tolerance window of 0.2 times the standard deviation of the respective time series ($r = 0.2$); and a lag value of 10, reducing the effective sampling rate to 10 Hz (Cavanaugh et al., 2006). Using the MatLab code, we obtained a single ApEn value for each trial, we then either used single values or averaged the data according to the method presented for ES above.

As a validation for the application of approximate entropy as a non-linear analysis tool, it needs to be identified if the COP time series data are deterministic. This is done by shuffling the data points using a transformation algorithm (Theiler, Eubank, Longtin, Galdrikian, & Farmer, 1992) in MatLab 2008r (Mathworks, Natick, MA). Using this transformation, a surrogate set of data was created. Surrogate and original data (ApEn) were then compared via t-tests ($\alpha = .05$). There were significant differences between the sets of data points for each pair of COP time-series, demonstrating non-random characteristics of the original time-series data.

Statistical analysis was performed using IBM SPSS Statistics 20.0. Mixed effects linear model analyses with polynomial contrasts of the repeated measures were used to test both dependent variables (ES, ApEn) for analysis of between-groups, within-groups, and interaction effects when comparing either baseline vs. first vibration trial (early effects), the nine vibration trials within days (short-term adaptation), or three testing days (long-term adaptation). Random effects for subjects were included in the models to account for dependency of the repeated measures. The model for testing early effects (first trial of vibration) on ES included heterogenous variances because the variances estimated from the observed data were substantially different; all other analyses were unadjusted since the observed data were consistent with homogeneous variance. The Huynh–Feldt epsilon was used as appropriate to adjust the degrees of freedom for deviation from sphericity of repeated measures.

3. Results

Eighteen participants completed the familiarization trials, baseline testing and three consecutive days of vibration tests. All participants assigned to the sway-referenced support condition were able to return to baseline (no vibration) performance within the vibration testing period, whereas no participant in fixed support was able to achieve a score within one standard deviation from baseline performance within the course of the testing period.

3.1. Early effects – equilibrium score

Data from the first trial of vibration exposure revealed an early effect on postural performance regardless of surface support condition (see Fig. 2) as measured by equilibrium score, $F(1,19.98) = 30.479$, $p < .001$. The equilibrium score in the fixed-support group decreased from a baseline value of 93.2 ± 2.3 to 67.4 ± 14.5, $F(1,8) = 26.044$, $p = .001$, and decreased from 74.0 ± 7.0 to 61.6 ± 12.9 in the sway-referenced support group, $F(1,8) = 10.010$, $p = .013$. There was no significant group-by-trials interaction effect, $F(1,19.98) = 3.742$, $p = .067$. There was a significant group effect, $F(1,19.98) = 13.221$, $p = .002$; scores in the fixed-support group were generally higher during baseline and initial vibration.

3.2. Short-term adaptation – equilibrium score

Analysis of short-term adaptation for the nine trials within each day under vibration showed no statistically significant changes of centered equilibrium score for Day 1, $F(6.85,109.64) = 1.076$, $p = .383$, Day 2 $F(7.02,112.31) = 1.327$, $p = .224$, and Day 3, $F(6.01,96.19) = 2.146$, $p = .055$. There was no group-by-trials interaction for Day 1, $F(6.85,109.64) = 1.503$, $p = .175$, Day 2, $F(7.02,112.31) = 0.286$, $p = .959$, and Day 3, $F(6.01,96.19) = 0.485$, $p = .818$. Fig. 3 illustrates that postural stability shows no evidence of adaptation within a testing day. The fixed-support group also displayed higher overall postural performance (i.e., higher equilibrium scores) compared to the sway-referenced support group.

3.3. Longer-term adaptation – equilibrium score

Longer-term adaptation over the three days increased the centered equilibrium score in both groups, $F(2,32) = 14.674$, $p < .001$ (see Fig. 3). There was a significant difference in centered ES between Days 1 and 2, $F(1,32) = 14.155$, $p = .001$ and between Days 2 and 3, $F(1,32) = 16.005$, $p < .0001$. No significant group-by-days interaction effect was found, $F(2,32) = .749$, $p = .481$; repeated administration of the test under vibration lead to similar improvements of balance performance in both surface condition groups. Over the course of the three testing days, both groups improved their postural control during vibration at the same rate. Centered equilibrium score differed significantly between groups, $F(1,16) = 1.149$, $p = .006$. Postural performance, unadjusted equilibrium scores, over the three testing days was overall higher in the fixed-support group (Fig. 3). However, Fig. 4 illustrates that the fixed-support group displayed significantly greater decrements (centered equilibrium scores) in response to vibration relative to their baseline measures when compared to the sway-referenced group.

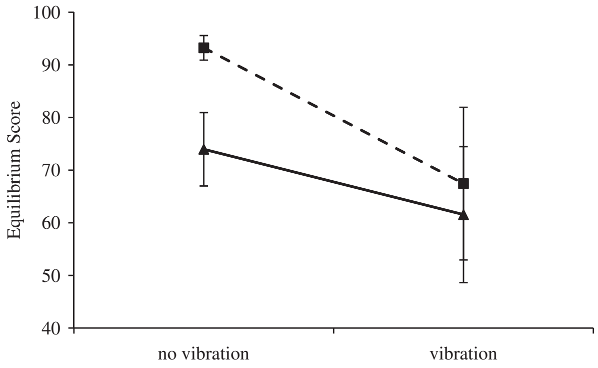

Fig. 2. Equilibrium Score (as a measure of postural stability, ranging from 0–100) means and standard deviation of fixed support condition (dashed line) and sway-referenced support condition (solid line) during both baseline testing and first vibration trial.

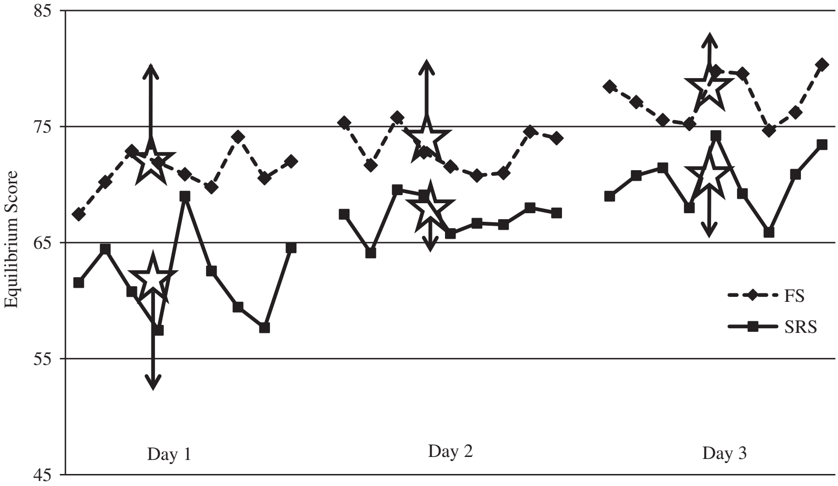

Fig. 3. Comparison of Equilibrium Scores in fixed-support condition (dashed line) and sway-referenced support condition (solid line) during nine vibration trials per day (27 trials total). Open stars represent the mean value (plus or minus one standard deviation) for the trials of a particular testing day.

3.4. Early effects – approximate entropy

There was a significant main effect of vibration, $F(1,16) = 5.386$, $p = .034$. Changes of approximate entropy were found only in the sway-referenced group (see Fig. 5) over the course of the first vibration trial. Approximate entropy values in the fixed-support group were 0.736 ± 0.149 without vibration and 0.794 ± 0.161 during initial vibration trial, $F(1,8) = 1.002$, $p = .346$. In the sway-referenced group, approximate entropy increased significantly from 0.740 ± 0.134 to 0.853 ± 0.206, $F(1,8) = 6.167$, $p = .038$. There was no group effect, $F(1,16) = 0.223$, $p = .643$ or time-by-group effect, $F(1,8) = 0.556$, $p = .467$.

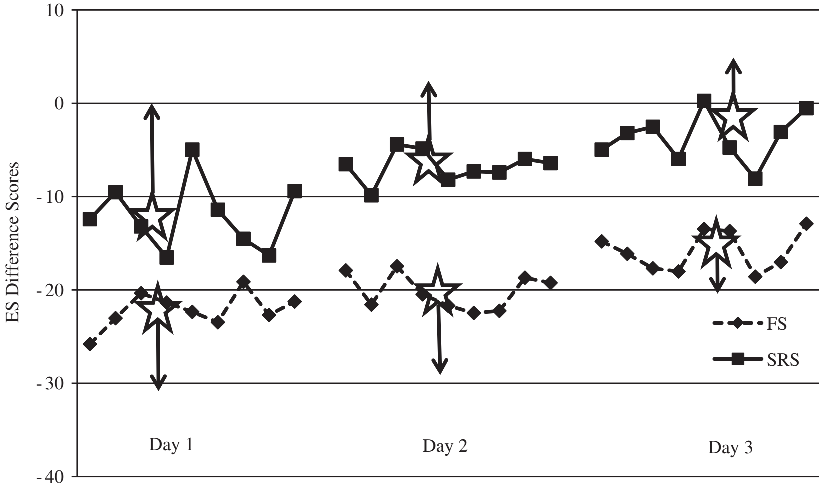

Fig. 4. Comparison of the difference scores between the baseline ES and the ES in fixed-support condition (dashed line) and sway-referenced support condition (solid line) during nine vibration trials per day (27 trials total). Open stars represent the mean value (plus or minus one standard deviation) for the trials of a particular testing day.

3.5. Short-term adaptation – approximate entropy

Analysis of short-term adaptation for nine trials within a day under vibration showed statistically significant changes of approximate entropy values for Day 1, $F(7.08,128) = 6.953$, $p < .001$, Day 2 $F(8,128) = 5.744$, $p < .001$, and Day 3, $F(8,128) = 2.434$, $p = .018$ (see Fig. 6). There was no group-by-trials interaction for Day 1, $F(6.85,128) = 1.612$, $p = .138$, Day 2, $F(8,128) = 0.865$, $p = .548$, and Day 3, $F(8,128) = 0.655$, $p = .730$; approximate entropy averages between groups were not developing differently between groups over the trials. Fig. 6 also illustrates that there was a general trend in both groups toward increasing regularity within a testing day and this trend was more pronounced in the fixed-support surface condition group. The fixed-support group also displayed more overall regularity (i.e., lower ApEn scores) compared to the sway-referenced support group.

3.6. Longer-term adaptation – approximate entropy

Repeated testing over days had no statistically significant effect on centered approximate entropy, $F(1.65,32) = 1.365$, $p = .269$ (see Fig. 6). There was no statistically significant group-by-days interaction effect, $F(2,32) = 2.915$, $p = .081$, indicating that neither group displayed long-term adaptation in this measure. Approximate entropy values were overall higher in the sway-referenced group, $F(1,16) = 9.306$, $p = .008$.

4. Discussion

In the present study, the influence of practice during a bipedal postural control task was investigated with different combinations of support surface stability and proprioceptive perturbation (Achilles tendon vibration). We sought to characterize both short and longer-term adaptation outcomes that would suggest compensation to the proprioceptive perturbation. Further, we used both linear and non-linear measures of force plate-derived COP data to explore features of postural control and adaptation that are not captured by traditional linear measures of postural performance.

4.1. Balance performance during baseline and first vibration trial

The observed baseline values exhibited the expected characteristics of postural stability under stable (FS) or unstable support (SRS) conditions: ES were significantly better in FS than in SRS. Standing

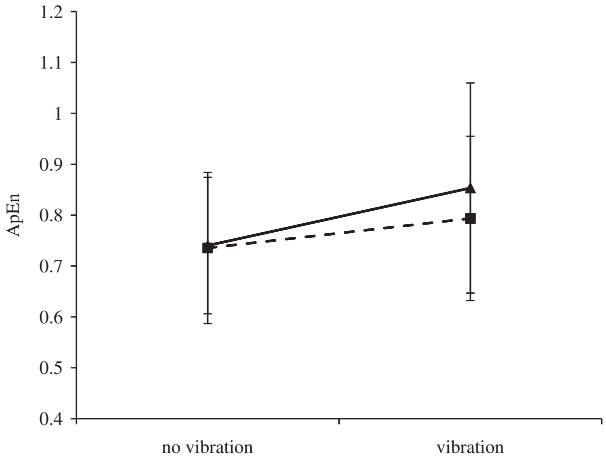

Fig. 5. ApEn (as a measure of sway regularity) means and standard deviation of fixed support condition (dashed line) and sway-referenced support condition (solid line) during both baseline testing and first vibration trial.

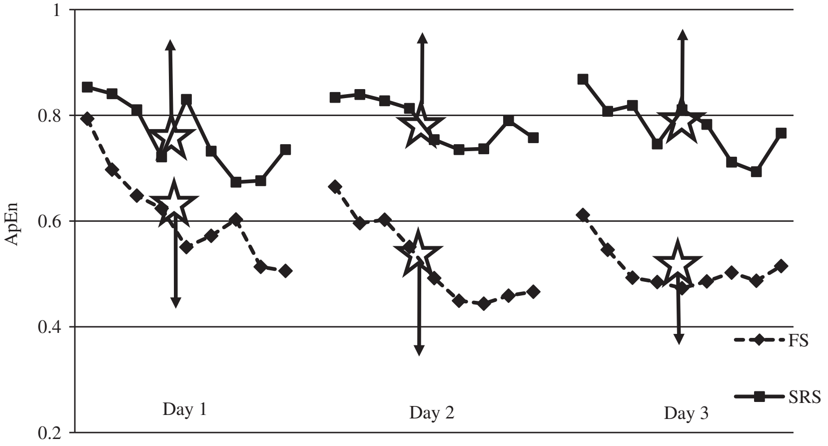

Fig. 6. Comparison of ApEn scores in fixed-support condition (dashed line) and sway-referenced support condition (solid line) during nine vibration trials per day (27 trials total). Open stars represent the mean value (plus or minus one standard deviation) for the trials of a particular testing day.

quietly on a stable surface provides more opportunity for retrieval of sensory information used in the control of bipedal posture. In the FS-condition without vibration, muscle spindles and mechanoreceptors of the soles of the feet are able to provide the CNS with reliable information related to postural sway that is used to regulate COP motion (Maurer et al., 2006). SRS reduces opportunities for obtaining reliable information to manage postural control, since reliable proprioceptive information is greatly minimized due to sway referencing. The early effects of ankle vibration on linear measures of postural control was considerably less in SRS (ES decreased by approximately 9%) compared to FS (ES decreased by approximately 28%). Although the group-by-trials interaction effect approached but failed to reach statistical significance ($p = .067$), the magnitude of the differences observed in both Fig. 2 and the difference between groups of the day 1 trial 1 deviation-from-baseline values plotted in Fig. 4 suggest that the support surface influences the response to vibration (see further discussion below).

4.2. Short- and longer term development of balance performance

Fransson and colleagues investigated adaptation effects in a series of postural task trials involving sensory perturbation in the form of musculo-tendon vibration (Fransson, Johansson, et al., 2003; Tjernström et al., 2005). They presented an explanation for the development of postural performance curves over time, based on several major factors: 1) a potential suppression of, or adaptation to vibration stimuli based on sensory reweighting and associated shift towards unperturbed afferents sources, 2) postural strategy changes including the potential modification of kinematic degrees-of-freedom by altering postural orientation, associated with changes in muscle co-contraction and ankle stiffness and 3) consolidation, representing longer-term changes of postural control based on motor memory and experience, that function to improve responses to applied constraints and perturbations. This explanation provides a framework in which to interpret the current data.

The equilibrium score data revealed no significant short term adaptation across the nine trials on a given day, regardless of condition. This finding suggests that during this short time period, potential postural control changes did not assist in reducing postural sway significantly. However, repeated administration of vibration over consecutive days led to improvements in ES in both support conditions and the rate of this improvement was similar. This finding suggests that with repeated exposure to vibration, adaptation did occur with the associated assumption that the postural control system was suppressing unreliable inputs and placing greater weight on more reliable sensory information. Repeated administration of postural tasks have shown to evoke reduction of body movements due to adaptation (Fransson, Johansson, et al., 2003; Nashner, Black, & Wall, 1982; Wrisley et al., 2007).

The current data are consistent with earlier work concerning the attenuation of the effects of muscle tendon vibration when a dynamic proprioceptive stimulus in the form of an unstable platform is added (Ivanenko et al., 1999). It has been proposed that this dampened response to vibration in the face of postural instability is the result of sensory down-weighting of ankle proprioceptive input. According to this hypothesis, unreliable input sources are less influential while integration of reliable sensory information is weighted more heavily for use in the maintenance of postural stability (Isableu et al., 2010; Oie, Kiemel, & Jeka, 2002; Vuillerme & Pinsault, 2007). Fig. 4 illustrates that the SRS group was less negatively impacted by the addition of vibration relative to the FS group, thereby suggesting they were potentially more effective in down-weighting the disrupted proprioception resulting from the application of vibration to the ankle musculature. Conversely, the FS group continued to be strongly impacted by vibration across all three testing days. This could be the result of the subjects continuing to attempt to rely on proprioceptive information that is normally reliable during fixed surface support conditions. The data do reveal that despite experiencing large performance decrements with vibration, the FS group did improve over the course of the three testing days, suggesting that consolidation was occurring.

The potential underlying mechanisms associated with reweighing of sensory input are not fully understood, but could be based on inhibitory spinal pathways or a process that suppresses the effect of increased firing of proprioceptive afferents under vibration when the muscle is being stretched (Bove, Nardone, & Schieppati, 2003; Radhakrishnan, Hatzitaki, Patikas, & Amiridis, 2011). This proposed reweighting process reflects an appropriate response to the decreased reliability of proprioceptive input associated with an unstable support surface that prevents one from optimally determining postural orientation. In the case of SRS, increased sway resulting from vibration would be attenuated relative to FS, due to decreased integration of unreliable ankle muscle spindle information for postural control. Additionally, due to the nature of the task in SRS, there is more postural sway and corresponding multiple muscle activation in the lower limbs. The increased extra-fusal activation might have an additional impact on attenuating vibrational effects, by unloading the spindle receptors and thereby affecting their firing rate (Radhakrishnan et al., 2011).

The observed effect would represent an example of the CNS's ability to down-weight or suppress single sensory information channels depending on their positive or negative influence on postural stability under specific conditions (Hatzitaki et al., 2004). There have been multiple approaches to determine the nature of sensory reweighting in postural control, but it remains unclear, to what extent presynaptic mechanisms, spinocerebellar- or higher motor processing contribute to the changes in weighting and integration of afferent information. The data presented in this study are consistent with the sensory reweighting hypothesis.

Our findings are in accordance with theories regarding the capability of the CNS to utilize different afferent information sources depending upon specific task demands and constraints. Over time, a refining of neuromotor processing improves functional postural control. In addition, mechanisms of consolidation (longer-term learning) are being utilized in order to improve postural balance (Tjernström, Fransson, Hafström, & Magnusson, 2002). As our criteria for learning the task was a return of ES within one standard deviation of initial baseline testing, only group SRS participants were able to fully adapt to the conditions and return to baseline. This suggests that the process of longer-term adaptation was more advanced in the SRS condition relative to FS. Although improvements were observed in FS as well, potential mechanisms of sensory reweighting, leading to postural control strategies shifts or motor learning were not sufficient to fully adapt to the perturbed sensory input emerging from ankle muscle spindles, at least not within the training period of three days. Since ES in FS still showed an upward trend at the completion of the three-day testing period, it would be interesting to investigate whether healthy participants could completely overcome muscle spindle perturbation on the stable support with additional practice.

4.3. Reflection of vibration effects and adaptation in sway regularity

The foundation of approximate entropy represents the predictability or repeatability of data points in a time series. An extensive summary of ApEn computation and potential applications is provided elsewhere (Stergiou, 2004). ApEn values approaching a value of 0 represent higher predictability and regularity of the data series, whereas values approaching 2 indicate less predictability or less regularity. ApEn as a non-linear tool to investigate biological systems has been used in a variety of settings (Cavanaugh et al., 2006; Pincus, Cummins, & Haddad, 1993). Previously, ApEn has been utilized for detection of potential adaptation effects, but not in a comparable setting to the current study. Regarding the interpretation of ApEn, there is a general consensus regarding regularity modifications associated with non-healthy, not fully developed or deteriorating systems. Overall, there seems to be a deviation from "normal levels" of regularity in affected biological systems, for example in Parkinson's disease posture. There could be a deviation from optimal control characteristics, accompanied by deviation of ApEn from an optimum, in either direction (Stergiou & Decker, 2011; Stergiou, Harbourne, & Cavanaugh, 2006). However, there is no standard, neurophysiological interpretation applied to the meaning of either increasing or decreasing ApEn values in a COP time series (Borg & Laxåback, 2010).

In the current study, the early influence of vibration was reflected in changes of ApEn in the sway referenced group only, a finding that is different from the result reported by Turnock and Layne (2010). These authors reported a significant decrease in ApEn scores relative to baseline during vibration trials conducted on a fixed support surface. This contrast between their data and the current data may result from differences in the analytical approaches between the former experiment and the current project. In our experiment, we compared baseline scores to scores of the initial trial of vibration testing. Conversely, Turnock and Layne assessed potential differences between vibration and no vibration using the mean of the first three vibration trials. It is possible that averaging over the first three trials resulted in masking some of the early effects of vibration on ApEn. When the current data are averaged over the first three vibration trials there is a slight decrease relative to the baseline score (0.712 to 0.736), despite the fact that the first vibration trial has an ApEn value of 0.793. What can be clearly observed in Fig. 6 is that the ApEn scores for the sway-referenced group decrease (increased regularity) across the nine trials, which is consistent with the Turnock and Layne findings of decreasing values during vibration testing on a fixed support surface. Both Figs. 6 and 7 illustrate that adaptation is occurring within a testing day, but unlike the equilibrium scores, there is no significant longer term adaptation occurring.

In addition to the potential mechanisms of adaptation discussed previously, it is also possible that the observed within day adaptation of ApEn for both groups may reflect a changing balance between the level of automatic control and attention invested in the task. Recent studies have provided evidence that ApEn changes when attention is focused on secondary tasks, and not consciously aimed

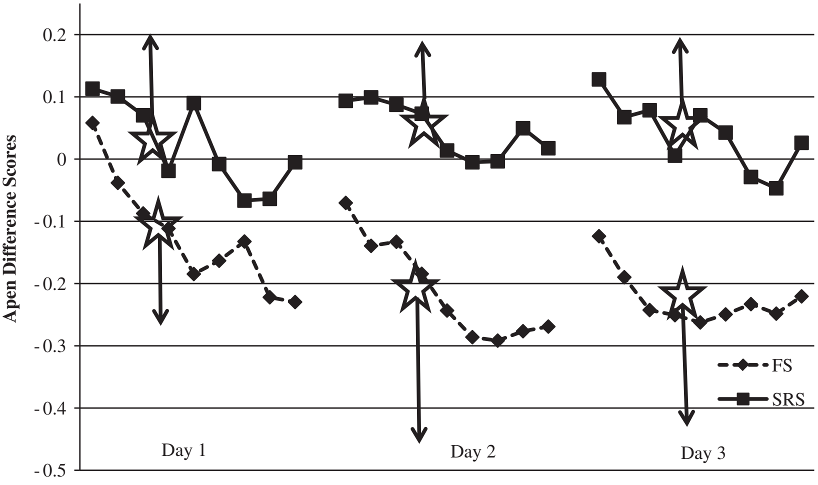

Fig. 7. Comparison of the difference scores between the baseline ApEn and the ApEn in fixed-support condition (dashed line) and sway-referenced support condition (solid line) during nine vibration trials per day (27 trials total). Open stars represent the mean value (plus or minus one standard deviation) for the trials of a particular testing day.

at the primary, postural task (Cavanaugh et al., 2007; Donker, Roerdink, Greven, & Beek, 2007; Stins, Michielsen, Roerdink, & Beek, 2009). It is plausible that the addition of vibration initially diverted attention from the task of maintaining quiet stance to focusing more on the vibration but over time, this attention was redirected back towards the postural control effort, thereby influencing both performance, as represented in ES, and modifying complexity, as represented in ApEn values.

Interestingly, the ApEn scores were noticeably lower in both the sway-referenced and fixed-support surface conditions in the Turnock and Layne paper when compared to the current data. This is likely the result of a methodological difference in the two protocols. Turnock and Layne activated the vibrators for 5 s prior to the initiation of the posture test while we simultaneously began vibration and posture testing. As mentioned above, our data captured the relatively large sway that results from the initiation of ankle musculature vibration and would therefore be reflected in higher ApEn scores (decreased regularity). The effect of postural assessment protocols on ApEn values may be a significant factor in differences observed in ApEn scores across the existing literature.

5. Conclusions

Our results show early and specific changes in postural control, depending on sensory context (availability of reliable proprioceptive input), external constraints (support surface characteristics) and interactions. We observed distinctive changes of neuromotor responses and control features based on repeated exposure to vibration and associated adaptation effects. However, the reflected changes depended on the respective support surface condition and the associated contextual, sensory constraints. Adaptations to muscle spindle stimulation were shown to be dependent on the characteristics of the surface indicating that support surface characteristics dictate, to some extent, the postural control processes involved in adaptation to Ia-afferent information perturbation.

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