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Improving postural control by applying mechanical noise to ankle muscle tendons

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Abstract

The application of subthreshold mechanical vibrations with random frequencies (white mechanical noise) to ankle muscle tendons is known to increase muscle proprioceptive information and to improve the detection of ankle movements. The aim of the present study was to analyze the effect of this mechanical noise on postural control, its possible modulation according to the sensory strategies used for postural control, and the consequences of increasing postural difficulty. The upright stance of 20 healthy young participants tested with their eyes closed was analyzed during the application of four different levels of noise and compared to that in the absence of noise (control) in three conditions: static, static on foam, and dynamic (sinusoidal translation). The quiet standing condition was conducted with the eyes open and closed to determine the subjects' visual dependency to maintain postural stability. Postural performance was assessed using posturographic and motion analysis evaluations. The results in the static condition showed that the spectral power density of body sway significantly decreased with an optimal level of noise and that the higher the spectral power density without noise, the greater the noise effect, irrespective of visual dependency. Finally, noise application was ineffective in the foam and dynamic conditions. We conclude that the application of mechanical noise to ankle muscle tendons is a means to improve quiet standing only. These results suggest that mechanical noise stimulation may be more effective in more impaired populations.

Keywords

Balance, Static and dynamic posture, Proprioception, Stochastic resonance, Healthy subjects

Introduction

Postural control is achieved through the integration of vestibular, visual, and somatosensory information. These sensory cues contribute to head/body orientation and stabilization in space. Under quiet standing conditions and in healthy subjects, the most sensitive information regarding body sway is provided by proprioceptive musculo-articular cues; cutaneous cues from the feet, legs, and torso; and visual cues (Fitzpatrick et al. 1994; Fitzpatrick and McCloskey 1994; Kavounoudias et al. 1998; Goble et al. 2009; Goble 2010; Lee et al. 2013). In healthy subjects, vestibular signals play a minor role. In the present study, we emphasized the role of muscle proprioceptive signals. More specifically, we investigated the consequences of proprioceptive optimization that was achieved through stochastic resonance, which is a counterintuitive phenomenon by which the addition of an optimal level of noise to a stimulus enables the detection of subthreshold events. Stochastic resonance has been described in a variety of physiological functions (reviews: Moss et al. 2004; McDonnell and Ward 2011). With respect to postural control, in healthy subjects, improved balance performance was reported for vestibular optimization that was achieved through vestibular stimulation with subthreshold electrical noise (Mulavara et al. 2011; Goel et al. 2015). When plantar skin information was optimized by applying vibrations to the soles of the feet, decreased body sway was also reported in healthy young and elderly individuals (Priplata et al. 2003; Lipsitz et al. 2015), patients with diabetes, and stroke patients (Priplata et al. 2006). Finally, the application of electrical noise to the anterior and/or posterior ankle muscles (Magalhaes and Kohn 2012; Magalhaes and Kohn 2014) or to the knee (Gravelle et al. 2002) reduced the amplitude of postural sways. The application of electrical noise to the ankle muscles is thought to result in stochastic resonance by increasing the sensitivity of leg muscle spindles, which then results in improved postural control.

In the present study, we chose to optimize ankle proprioceptive cues by applying mechanical noise to ankle muscle tendons. We used this method because the effects of mechanical stimulation on neuromuscular function have been accurately described and provide a solid basis for understanding the potential postural effects. Indeed, improved movement detection due to the induction of stochastic resonance by mechanical stimulation was recently demonstrated for the first time (Ribot-Ciscar et al. 2013). More specifically, the application of an optimal-amplitude random mechanical vibration to both the extensor and flexor ankle muscle tendons was shown to improve the detection of imposed ankle movements that were initially subthreshold. In addition, microneurographic recordings revealed improved muscle spindle responses during the application of an optimal level of mechanical vibration to muscle tendons (Cordo et al. 1996; Ribot-Ciscar et al. 2013). In the present study, mechanical noise was applied to both the gastrocnemius/soleus (GS) muscles and the tibialis anterior (TA) muscle to optimize ankle proprioceptive cues.

In addition, even in a simple postural condition such as standing quietly on a firm support in a stable visual environment, interindividual variability has been reported in healthy subjects, *i.e.*, each person relies differently on the sensory information available for postural control. Comparative analysis of postural sway with eyes open (EO) and eyes closed (EC) revealed the different weighting the subjects applied to visual cues for the maintenance of static postural control. With EC, some subjects displayed larger postural sway, whereas for others, the oscillations were reduced (Lacour et al. 1997; Borel et al. 2008). Such individual differences may reflect the differential use of proprioceptive information for the control of static posture. Therefore, in the present study, we sought to determine whether the consequences of ankle proprioceptive optimization were modulated according to individual sensory strategies for postural control. To determine the postural consequences of ankle proprioceptive optimization, we applied different levels of noise and compared the postural performance effects of each noise level to a control without noise. Postural performance was analyzed using posturographic and motion analysis evaluations.

Another main issue was to specify whether the effects of mechanical noise depended on the difficulty of postural control. Indeed, the natural activation of muscle spindles differs according to postural condition, and the consequences of mechanical noise may vary accordingly. Stochastic resonance may increase the number of recruited muscle spindles and/or their sensitivity. Therefore, applying mechanical noise to ankle muscle tendons may have differential effects under static and dynamic conditions. In addition to during the static quiet standing condition, the effect of noise was also analyzed while the subjects were standing on a foam block and in a dynamic condition that consisted of sinusoidal anteroposterior translations.

Materials and methods

Participants

Twenty healthy young subjects were included: 7 men (aged 26.4 ± 2.4 years (mean ± SD); body weight: 67.4 ± 7.5 kg) and 13 women (aged 27.6 ± 6.0 years; body weight: 63.1 ± 10.9 kg). All participants met the following inclusion criteria: no previous physical, neurological, or sensory disorders; no medication that might influence balance; and no musculoskeletal impairment in the past 2 years. Each participant provided written informed consent prior to their inclusion in the study, and the study was approved by the local ethics committee (CPP Sud Méditerranée I # 14 001).

Experimental protocol

The experiments were conducted while the participants stood quietly without making voluntary gestures and with their hands held in a natural position along the vertical body axis. The participants stood barefoot on a force plate mounted on a translator (Synapsys, Marseille, France) with their feet shoulder-width apart. The participants were tested under three postural conditions with EC. In the first *(static condition)*, postural performance was evaluated on the motionless force plate by asking the participants to stand straight. In the second *(foam condition)*, balance performance was measured while the participants stood on a 6-cm-thick foam pad (Airex Balance Pad); this condition was aimed at generating larger body oscillations. In the third *(dynamic condition)*, the participants were tested on a moving platform that made sinusoidal anteroposterior translations with an amplitude of 7 cm and a frequency of 0.25 Hz. Twelve oscillation cycles were completed per trial. The participants were asked to keep their balance and avoid stepping. In all postural conditions, a special device prevented them from falling in case they lost their balance. The 3 postural conditions (static, foam, and dynamic) were run in random order. In each postural condition, 5 noise levels (B0, B1, B2, B3, and B4) were randomly used. In addition, in the static condition, 3 more trials were performed with EO to determine the weighting of visual input in the postural control of each participant.

Noise stimulation was synchronously initiated with the recording of posturographic and motion analysis data and was stopped at the end of the recording (trial duration: 51.2 s). Each participant completed the three experimental sessions on the same day, and each of the sessions included one postural condition and five noise levels; each noise was repeated three times. All of the participants completed all of the postural conditions. To rule out the effect of fatigue, a 20-s delay was included between each consecutive trial; during this delay, the participants were required to move their ankles and knees. In addition, a 5-minute rest period, during which the participants sat on a chair, was observed every six trials. Considering potential carry-over effect, this delay may be too short but may have been minimized by randomizing conditions and noise stimulation intensities. To avoid surprise and startle responses, in each experimental condition, the participants completed one trial before the start of data acquisition.

Mechanical noise stimulation

During quiet standing, the TA muscle is mostly passive, whereas the GS muscles are generally active (Aniss et al. 1990). Consequently, muscle proprioceptive information that originates from the TA muscle is related only to ankle movement, while that arising from the GS muscles is also due to the contraction of intrafusal muscle fibers (Hulliger et al. 1985; al-Falahe et al. 1990; Ribot-Ciscar and Roll 1998). For this reason, it is generally agreed that TA muscle proprioceptive information is principally involved in the coding of ankle movements (Di Giulio et al. 2009), and it may seem reasonable to apply mechanical noise to these muscles only. However, because the proprioceptive role of the anterior and posterior leg muscles may also change according to the direction of postural oscillations, we chose to simultaneously vibrate the TA and GS muscle tendons.

Two light vibrating elements (C-2 tactor, Engineering Acoustics, Winter Park, FL, USA) were strapped to both ankles over the distal tendon of the TA and GS muscles with soft elastic tape. The noise generator consisted of a single-chip record/playback device that delivered a digitized white noise signal band-pass filtered at 100-300 Hz (Priplata et al. 2003). The noise was applied at levels that were called B1, B2, B3 and B4, which corresponded to an amplitude with a root mean square of 20, 30, 100, and 280 μm, respectively. The absence of noise, *i.e.*, the control trial, was referred to as B0. The same stimulation signals were simultaneously delivered to both the TA and GS muscle tendons. Noises at the two lower levels were not perceived, while those at the two higher levels were slightly-to-clearly perceivable.

Data acquisition and processing

Postural control was assessed by means of posturography and motion analysis evaluations.

Posturographic evaluation of postural performance

In each of the three postural conditions, 51.2-s recordings were acquired. The center of foot pressure (CoP) displacement was sampled at 40 Hz in the static and foam conditions and at 100 Hz in the dynamic condition. The recordings were processed using PosturoPro software (Framiral, Cannes, France) to analyze the postural sway of the participant. Body sway was analyzed by CoP displacement in the anteroposterior direction. Postural performance was quantified using both the CoP area (the area of the confidence ellipse including 95% of the CoP displacements, mm^2) and the wavelet transformation (time-frequency analysis), which is a more accurate non-linear analysis of the CoP displacement processing of the postural data (Lacour et al. 2008; Bernard-Demanze et al. 2009; Young et al. 2012). The wavelet transformation method provides a three-dimensional representation of body sway: the CoP displacement frequency as a function of time, and as a third dimension, the spectral power is represented by a color code (“hot” colors for high powers and “cold” colors for low powers). The wavelet analysis enabled us to compute the mean spectral power for all frequencies over the entire recording time. The mean spectral power density of the recorded signal was divided into three frequency bands (0.05–0.5 Hz, 0.5–1.5 Hz, and 1.5–10 Hz; arbitrary units: AU). These steps in the analysis of body sway are illustrated in Figure 1.

(Figure 1 about here)

Motion analysis evaluation of postural performance

Motion recordings were made along with the postural recordings of CoP displacements. Body stabilization was recorded using a video motion analyzer (Codamotion, Charnwood Dynamics, UK). Six active markers were placed on the head (in infraorbital and acoustic meatus positions), acromion, iliac crest, patella, and ankle on one side of the body. Two supplementary markers were also placed on the platform. Marker positions were sampled every 10 ms (100 Hz). In our experimental setup, the overall accuracy of marker angular position was ~0.02°. For all postural conditions, body segment angular displacements were measured in the XY, XZ, and YZ planes and computed from the position of each active marker. The two markers placed on the head allowed the Frankfurt plane to be defined. Head stabilization was defined as the variance of each angle (Tardieu et al. 2009). In the dynamic condition, the gain of head compensatory control was computed as the ratio of head motion in space to platform motion. Similar calculations were made to obtain trunk (acromion and iliac crest), hip (iliac crest and patella), and knee (patella and ankle) stabilization and gain.

Sensory strategy for posture control

Based on the hypothesis that the effects of mechanical noise stimulation may depend on the weighting of sensory information for postural control, we quantified the weighting of visual cues for postural quality control in each participant. To accomplish this, we used the mean Percentage Difference of postural Sway (PDS) as evaluated by the ratio [(EC area-EO area)/(EC area+EO area)x100] (Lacour et al. 1997). Positive values indicate larger-amplitude body sway with EC compared to EO, suggesting a major contribution of visual cues to postural control (referred to as a visual postural strategy). In contrast, negative values indicate smaller-amplitude body sway with EC compared to EO, suggesting that the participant did not rely on visual cues to control their posture (referred to as a nonvisual strategy). The mean PDS was calculated for the static postural condition.

Statistical analyses

For each participant, each noise was applied three times in each experimental condition. The average of the 3 measurements obtained for each variable was analyzed. The parameters used in the posturographic evaluation of postural performance through body sway (CoP area and the spectral power density of the three frequency bands) were analyzed using Friedman ANOVAs and post hoc Wilcoxon tests. We used nonparametric statistics because the data did not meet the normality requirement of

ANOVA, as revealed by Shapiro-Wilk test. The effects of gender and visual dependency were evaluated in the control trial (without noise) and when noise was applied using the Mann-Whitney U test. For each of these parameters, the data obtained for the different noise levels (B0, B1, B2, B3, and B4) were compared. Separate ANOVAs were performed for all three postural conditions (static, foam, and dynamic). The motion analysis postural performance data were analyzed by using ANOVAs to compare the displacement of the different markers located on the body. ANOVAs were also used to compare body segment (head, trunk, hip, and knee) stabilization between all three postural conditions. For the dynamic postural condition, an additional ANOVA was used to analyze the effect of noise through the gain of the head, trunk, hip and knee. The results were considered statistically significant at $p<0.05$.

Results

Noise stimulation effect on postural performance in the static condition

The wavelet transformation data reported for the anteroposterior direction showed that the mean spectral power density in the first frequency band (0.05 to 0.5 Hz), which corresponded to the slowest movements, was significantly lower when mechanical noise was applied compared to control (absence of noise: B0) (Friedman ANOVA, $\text{Chi}^2_{(20, 4)}=10.16$; $p<0.04$), indicating a lower energetic cost. These data indicate that postural control improved when mechanical noise was applied. More detailed analysis revealed that the effect of noise was significant only for B2 (Wilcoxon test, $p<0.02$), with a mean decrease in spectral power density of 30.4±13.8% (Fig. 2). For the middle frequency range (0.5-1.5 Hz), the mean spectral power density noise stimulation was 15±19.7% lower for B2 than B0. However, this difference was not significant ($p=0.41$). For the highest frequency range (1.5-10 Hz), the mean spectral power density for the B2 noise stimulation was significantly lower than that for B0 ($p<0.02$), with a mean decrease of 22.6±9.0%. The data analysis also indicated that most of the signal power was in the low frequency band (Fig. 1). The mean spectral power density of body sway recorded in the low, medium, and high frequency bands represented 93.8%, 5.9%, and 0.3%, respectively, of the total spectral power density of body sway. Because the B2 noise significantly improved postural control, B2 was defined as “optimal” compared to the other noise levels. A systematic check indicated that this noise level was not perceived. Statistical analysis performed on the wavelet transformation data reported for the mediolateral direction showed no significant effect of noise for all three frequency bands. Finally, the traditional posturography data were less discriminating since the variance analysis showed that the CoP area did not significantly differ between the noise stimulation and control without noise.

(Figure 2 about here)

ANOVA of the motion analysis data showed that neither the head stabilization nor the stabilization of the other body segments differed between the various mechanical noise stimulations. Figure 3 illustrates the head stabilization, *i.e.*, the head angular displacement in the three spatial planes (sagittal, frontal and horizontal). Similar results were obtained for trunk, hip and knee stabilization. Thus, in our young and healthy participants, the improved postural performance, as demonstrated by the reduced spectral power density, was not associated with improved head or other body segment stabilization in space.

(Figure 3 about here)

The effect of noise on postural control, as evaluated using the spectral power density parameter, indicated considerable interindividual variability: the standard deviations were large, suggesting that the noise effect varied among the participants. To pinpoint individual differences in the effect of noise stimulation on postural performance, we evaluated the correlation between the noise effect and postural performance without noise. The noise effect was expressed as the ratio between the spectral power density for B0 (without noise) and spectral power density for B2 (the optimal noise level). These data are illustrated in Figure 4 and revealed a positive correlation between the noise effect and postural performance without noise (Pearson r=0.56; $p<0.01$) for individual mean data. In other words, the effect of noise stimulation on postural performance in the static condition depended on individual postural performance without noise: the higher the spectral power density for B0, the greater the noise effect.

(Figure 4 about here)

To evaluate the sensory strategy used for posture control, we quantified the weighting of visual cues for postural control in the static condition. For each participant, body sway area with EO and EC was compared using the PDS. The PDS allowed us to directly compare the participants and to rank them along a continuum whose extremes were between 100 and -100. The histogram in Figure 5 shows the distribution of PDS values. Ten participants (visual participants) exhibited a positive mean PDS of 21.2±19.4% (mean±SE) (range 4 to 65%). They swayed more with EC than with EO; therefore, visual cues played a major role in the postural control strategy of these participants (*i.e.*, they used a visual strategy to control their posture). The remaining 10 participants (nonvisual participants) showed a negative mean PDS of -20.1±11.9% (range -1 to -35%). They swayed less with EC than with EO, indicating that they did not rely on visual cues to control their posture (*i.e.*, they used a nonvisual strategy to control their posture).

A Mann-Whitney test performed on the spectral power density without noise (B0) indicated that there was no effect of sensory strategy for postural control in our participants (Z=1.74; *p*=0.08). Moreover, the effect of noise did not significantly differ between the visual and nonvisual participants (Z=0.26; *p*=0.79). Therefore, the individual differences in the effect of mechanical noise stimulation on postural performance described above were not related to the sensory strategy that the participants' preferentially used for postural control. Additionally, the interindividual variability was not explained by the participants' gender because no gender effect was found for B0 (Z=0.36; *p*=0.75). The effect of noise was also similar in women and men (Z=1.18; *p*=0.23).

(Figure 5 about here)

Effect of noise stimulation on postural performance in the foam and dynamic conditions

A comparison of the effect of the optimal noise on postural control in the different postural conditions is illustrated in Figure 6. In the foam condition, a Wilcoxon test indicated the absence of significant changes in spectral power density in the anteroposterior direction during mechanical noise stimulation compared to during the absence of noise. However, a trend towards significance (p=0.07) was found in the lower frequency band (0.05–0.5 Hz), with a mean decrease in spectral power density of 13.1±15.3% for B2 noise stimulation compared to B0. In the 0.5–1.5 Hz and 1.5–10 Hz frequency bands, no significant differences in spectral power density were found between B0 and B2. Statistical analysis of the wavelet transformation data for the mediolateral direction revealed the absence of a significant effect of noise for all three frequency bands. These data were associated with the absence of difference in head, trunk, hip and knee stabilization between B0 and B2.

In the dynamic condition, when the platform was sinusoidally translated in the anteroposterior direction, the application of noise to the ankle tendons did not induce postural changes. This was true for the mean spectral power density, which did not significantly differ between the optimal noise (B2) and without noise (B0) conditions for any of the frequency bands in both the anteroposterior and mediolateral directions. Finally, as shown in Table 1, the gain of the head, trunk, hip, and knee remained unchanged, regardless of the noise level applied.

(Table 1 & Figure 6 about here)

It is noteworthy that in the foam and dynamic conditions, the participants displayed larger-amplitude body sways to maintain their balance. Compared to those in the static condition, the spectral power density values were significantly larger in the foam condition, ($Chi^2_{(20,\ 9)}$=140.6; p<0.00001) as were the linear displacements in the anteroposterior direction of the markers located on the body ($F_{(1,19)}$=124.72; p<0.00001 for the head, trunk, hip, knee, and ankle) (Fig. 6). Such displacements result from both rotation and/or translation of the body segment supporting the markers. In the dynamic condition, the spectral power values were increased even farther over those in both the static ($Chi^2_{(20,\ 9)}$=139.4; p<0.00001) and foam ($Chi^2_{(20,\ 9)}$=133.4; p<0.00001) conditions. Similar findings were observed for the markers' linear displacements in the anteroposterior direction ($F_{(1,19)}$=2637.67; p<0.00001 and $F_{(1,19)}$=640.14; p<0.00001 for the static and foam conditions, respectively) (Fig. 6). In the foam and dynamic conditions, the mean ankle linear displacement in the anteroposterior direction was increased by a factor of 5.7 and 94.2, respectively, and the mean knee linear displacement was increased by a factor of 3.0 and 12.6, providing evidence of a major increase in leg movements in these conditions compared to the static postural condition. For comparison, the linear displacement of other body parts was also increased but to a lesser extent: by a factor of 2.8 and 6.8 for the hip and by a factor of 2.4 and 4.8 for the head. This increase in leg movements may account for the differential effects of mechanical noise stimulation on postural performance in the different postural conditions.

Discussion

This study investigated the effect of the application of mechanical noise to ankle muscle tendons on postural control in healthy young adults as well as the consequences of increasing postural difficulty. The effects of ankle proprioceptive optimization during different postural conditions (static, foam and dynamic sinusoidal anteroposterior translation) were studied while the participants' eyes were closed. Postural performance was analyzed for different noise levels using posturographic and motion analysis evaluations. The effects of different noise levels were compared to a control response without noise.

1. The application of mechanical noise to ankle muscle tendons improves postural control during the maintenance of an upright stance

In the present study, the wavelet transformation data demonstrated a reduction in the spectral power density of body sway in the anteroposterior direction specifically in the frequency bands that corresponded to the slowest and fastest movements. In the middle frequency band, an average reduction was observed, but it did not reach significance. These results highlight a decrease in the energetic cost of maintaining an upright stance during the application of mechanical noise to the ankle muscle tendons. Postural improvement was reported only for the B2 noise level, which corresponded to stochastic stimulation with a mean amplitude of 30 µm and was referred to as the optimal noise level. This noise level was not perceived, ruling out the possibility that attentional changes affected postural control during ankle stimulation. The improvement of postural performance was not significant when it was evaluated based on CoP area. This finding confirms our previous data indicating that non-linear analyses are more discriminating than the classical parameter of CoP area (Bernard-Demanze et al. 2009; Young et al. 2012). However, during quiet standing, no significant differences in body segment stabilization were reported between the B2 noise level and the control without noise. These results are probably related to the fact that the participants tested in this study were young and healthy and therefore had good balance and could easily maintain an upright stance in the static condition. Stabilization of the head and other body segments may have already been optimal. We demonstrated that the stabilization of head and other body segments remained unchanged even in the participants whose body sway showed the greatest improvement.

In a previous study that used the same methodology, we showed that the application of mechanical noise to the ankle muscle tendons improved the detection of the direction of imposed movements that were initially subthreshold (Ribot-Ciscar et al. 2013). More specifically, the optimal level of noise, which was associated with the best discriminative performance of movement direction, was the same as the one that led to the best postural performance in the current study (B2 noise level). The effect of the application of mechanical noise can be explained by stochastic resonance. As a simple explanation, the addition of optimal noise leads to small membrane potential fluctuations that cause receptors to reach threshold for stimuli that were initially subthreshold (Volgushev and Eysel 2000). Therefore, the noise effect found here presumes the presence of muscle spindles that are not recruited by the ankle displacements and that these muscle receptors are close to threshold, which is then surpassed due to the application of noise. These hypotheses are rooted in microneurographic recording-based demonstrations of improved muscle spindle responses during noise stimulation (Cordo et al. 1996; Ribot-Ciscar et al. 2013). However, the possibility that proprioceptive information of cutaneous origin might also be improved cannot be completely ruled out.

This type of increase in the number of recruited proprioceptors increases proprioceptive feedback, which, in turn, improves the detection of ankle movements and, ultimately, postural performance.

An improvement in static postural control via stochastic resonance is consistent with previous reports of the enhancement of plantar cutaneous information by mechanical noise (Priplata et al. 2003; Priplata et al. 2006) and by noisy electrical stimulation of the vestibular system (Mulavara et al. 2011; Goel et al. 2015). More particularly, the present results agree with the studies of Magalhaes and Kohn (Magalhaes and Kohn 2012; Magalhaes and Kohn 2014) and Gravelle and collaborators (Gravelle et al. 2002), which investigated the effect of electrical noise stimulation of the ankle and knee muscles, respectively.

In addition, the present results revealed considerable interindividual variability. We found that the effect of noise stimulation on postural performance in the static condition depended on individual postural performance in the absence of noise. The greater the body sways in the absence of noise, the greater the noise effect. These results are consistent with stochastic resonance. We suggest that the larger the participant’s postural oscillations, the greater the number of muscle spindles near threshold, and the more the addition of noise improves movement coding and postural performance. This type of baseline-dependent effect of stochastic mechanical stimulation has been described for postural variability (Priplata et al. 2006; Kelty-Stephen and Dixon 2013) as well as for spatial stride-to-stride variability in gait (Galica et al. 2009; Stephen et al. 2012), *i.e.,* stochastic resonance results in greater reductions in variability in subjects with greater baseline variability. Our data suggest that individual differences in the effect of mechanical noise stimulation on postural performance are not based on the participants' preferred sensory strategy for postural control. Stated another way, the effect of mechanical noise stimulation does not depend on the initial weighting of visual and proprioceptive cues in the absence of noise.

2. Mechanical noise is ineffective in more challenging postural conditions

Because the application of mechanical noise to ankle muscle tendons can be used to facilitate an upright stance, we were even more interested to investigate this effect under more challenging postural conditions. Our results showed that when postural difficulty was increased through the use of a foam pad or by sinusoidally translating the support platform in the anteroposterior direction, the application of mechanical noise was ineffective, *i.e.*, body sway was not significantly improved compared to that observed without noise. In both the foam and dynamic conditions, these data were confirmed by motion analysis, which showed that head and body segment stabilization remained unchanged during the noise stimulation. Note that in the foam condition, although noise-induced changes tended to decrease the spectral power density in the lower frequency band, the trend did not reach significance (p=0.07).

Under conditions of decreased stability, such as in the foam and dynamic conditions, ankle displacements are larger, resulting in greater recruitment of anterior and posterior leg muscle spindles. Consequently, the number of muscle spindles that were silent in the absence of noise and likely to be recruited during the application of noise was probably very small in the foam condition and even smaller in the dynamic condition; this small number of available muscle spindles would explain the absence of noise-induced postural improvement. Moreover, muscle spindles recruited by suprathreshold movements may elicit movement-induced responses contaminated by vibration-induced responses (Roll et al. 1989). This type of mixed response to both vibration and movement has been previously demonstrated to degrade upright standing in young as well as older adults (Hay et al. 1996) and may be partially responsible for the absence of improvement observed in the dynamic condition in the present study.

Conclusion

In summary, we showed that the application of subthreshold mechanical noise to the ankle muscle tendons improves postural control during quiet standing. The effect of the application of mechanical noise can be explained by stochastic resonance. The underlying mechanism involves an increased recruitment of proprioceptors and especially muscle spindles. The increased recruitment of muscle spindles increases proprioceptive feedback, which, in turn, improves postural performance. We reported considerable variability in the effects of mechanical noise stimulation among the participants. This variability depends on the initial body sway: the greater the amplitude of body sways in the absence of noise, the greater the noise effect. Moreover, a fixed noise (*i.e.*, not adjusted to the muscle spindle sensory threshold) may have different effects in different people and may account for the variability of postural responses observed among our participants. This variability also does not seem to be based on the participants' preferred sensory strategy for postural control. Furthermore, we found that the effect of mechanical noise stimulation was ineffective in more challenging postural conditions.

These results identify possible mechanisms for the effects of subthreshold mechanical stimulation of the ankle muscle tendons. Because a better postural response was obtained in the healthy young subjects, more consistent improvement can be expected in persons with balance problems. This may be the case for older adults in whom ankle proprioceptive acuity is impaired (Goble et al. 2009) and in patients with vestibular deficits that are not fully compensated because they favor visual cues

(Guerraz et al. 2001), which could negatively impact proprioceptive cues. For patients, mechanical stimulation may also be effective in more challenging postural conditions due to the reduced involvement of muscle spindles in the maintenance of balance as well as during complex tasks that involve increased cognitive load (Keshner et al. 2014). All of these considerations suggest that subthreshold mechanical noise stimulation may be a simple tool to facilitate the rehabilitation of patients with postural deficits.

Figure legends

Fig. 1: Posturographic recording analysis for the static, foam, and dynamic postural conditions. *Top*: CoP displacement in the anteroposterior direction. *Middle*: three-dimensional chart obtained by wavelet analysis. Time is represented on the abscissa, while frequency is represented on the ordinate. Spectral density power is color coded. *Bottom:* spectral density power versus frequency plot.

Fig. 2: Effect of mechanical noise stimulation on postural performance in the static postural condition. Spectral power density in the three frequency bands for the different noise levels (B0: no noise, B1: 20 µm, B2: 30 µm, B3: 100 µm, and B4: 280 µm). Vertical bars represent the standard error. Significant differences between noise levels are indicated by asterisks.* $p<0.05$. Note that B2 is the optimal noise level.

Fig. 3: Effect of mechanical noise stimulation on head stabilization. Head stabilization in the three spatial planes for the five noise levels in the static postural condition.

Fig. 4: Correlation between the amplitude of the effect of noise and the initial postural stability in the static condition for each subject. Abscissa: the effect of noise corresponds to the ratio between the spectral power density for B0 and B2. Ordinate: the postural stability corresponds to the mean spectral power density in the control test (without noise). Both types of measures correspond to the low frequency band (0.05-0.5 Hz).

Fig. 5: Individual sensory strategies used for posture control. Histogram of the number of participants in bins of 10% that represent the percentage difference of sway (PDS) with eyes closed compared to eyes open in the static postural condition.

Fig. 6: Effect of mechanical noise stimulation on postural performance in the static, foam, and dynamic postural conditions. *Top:* posturographic evaluation of postural performance. Comparison of the mean spectral power density in the 0.05- to 0.5-Hz frequency band for postural performance without noise (B0) and with the optimal noise level (B2). The same conventions used in Fig. 2 are applied. *Bottom*: motion analysis evaluation of postural performance. Schematic representation of a participant standing on the platform. The mean displacement of markers on the head, shoulder, hip, knee, and ankle over all of the participants, as reported for postural responses without noise (B0).

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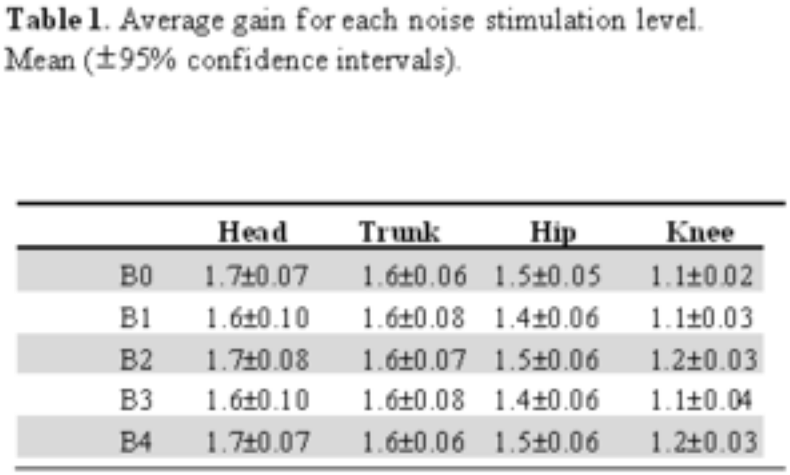

Table 1. Average gain for each noise stimulation level. Mean (±95% confidence intervals).

	Head	Trunk	Hip	Knee
B0	1.7±0.07	1.6±0.06	1.5±0.05	1.1±0.02
B1	1.6±0.10	1.6±0.08	1.4±0.06	1.1±0.03
B2	1.7±0.08	1.6±0.07	1.5±0.06	1.2±0.03
B3	1.6±0.10	1.6±0.08	1.4±0.06	1.1±0.04
B4	1.7±0.07	1.6±0.06	1.5±0.06	1.2±0.03

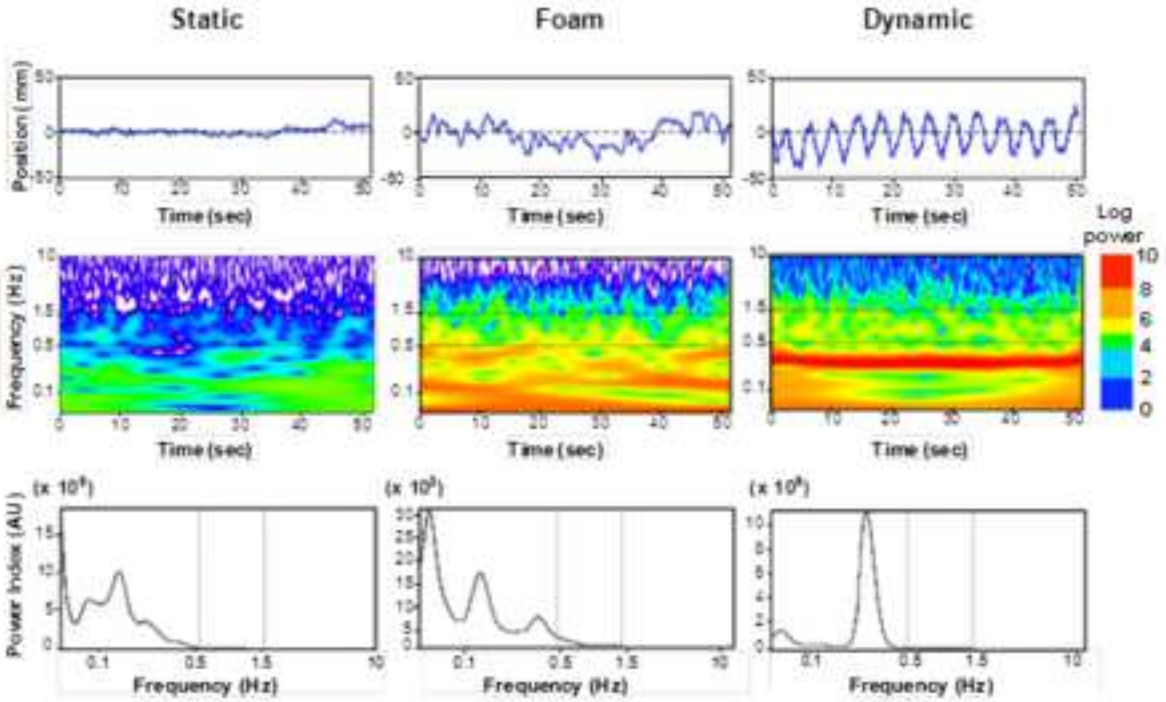
Static
Foam
Dynamic
Position (mm)
50
0
-50
0
10
20
30
40
50
Time (sec)
Log power
10
8
6
4
2
0
Frequency (Hz)
10
1.5
0.5
0.1
Power Index (AU)
15
10
5
0
30
25
20
Frequency (Hz)

Figure 1

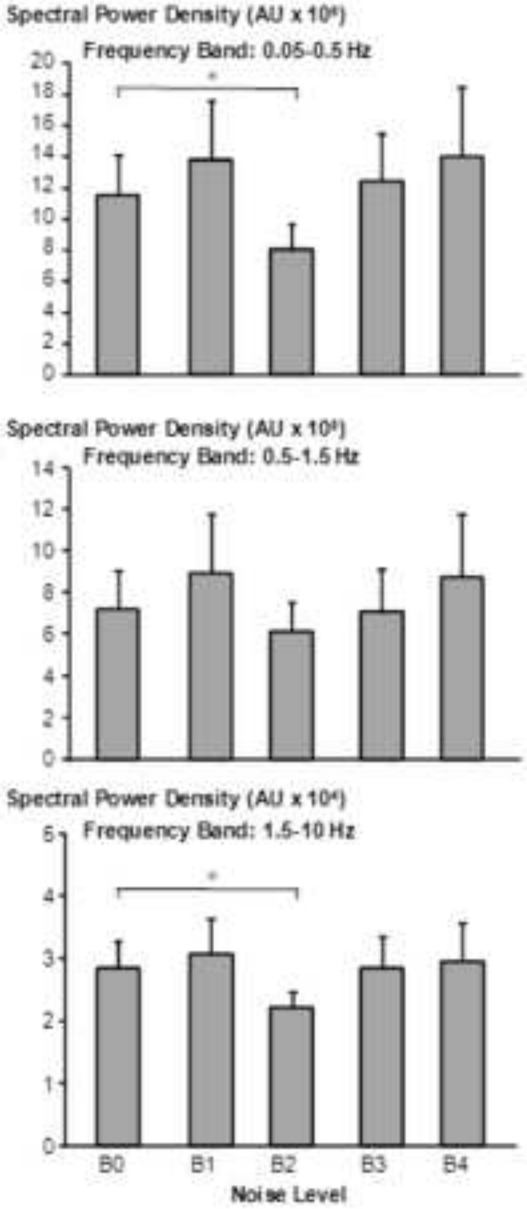
Spectral Power Density (AU x 10^6)
Frequency Band: 0.05-0.5 Hz
20
18
16
14
12
10
8
6
4
2
0
*
Spectral Power Density (AU x 10^5)
Frequency Band: 0.5-1.5 Hz
14
12
10
8
6
4
2
0
Spectral Power Density (AU x 10^4)
Frequency Band: 1.5-10 Hz
5
4
3
2
1
0
*
B0
B1
B2
B3
B4
Noise Level

Figure 2

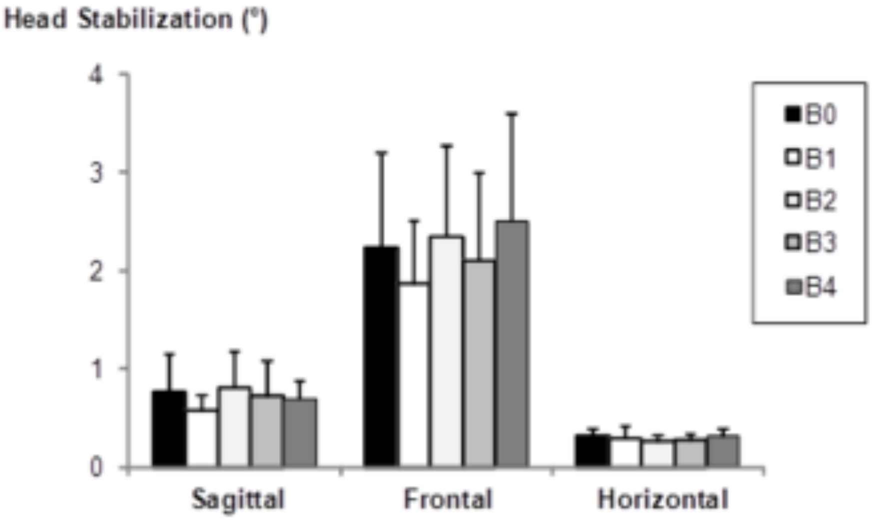
Head Stabilization (°)
4
3
2
1
0
Sagittal
Frontal
Horizontal
B0
B1
B2
B3
B4

Figure 3

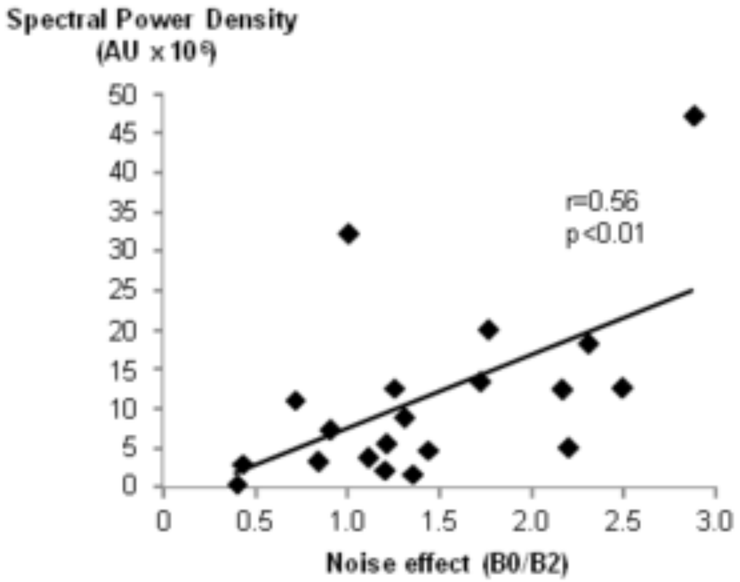
Spectral Power Density
(AU x 10^6)
50
45
40
35
30
25
20
15
10
5
0
r=0.56
p<0.01
0
0.5
1.0
1.5
2.0
2.5
3.0
Noise effect (B0/B2)

Figure 4

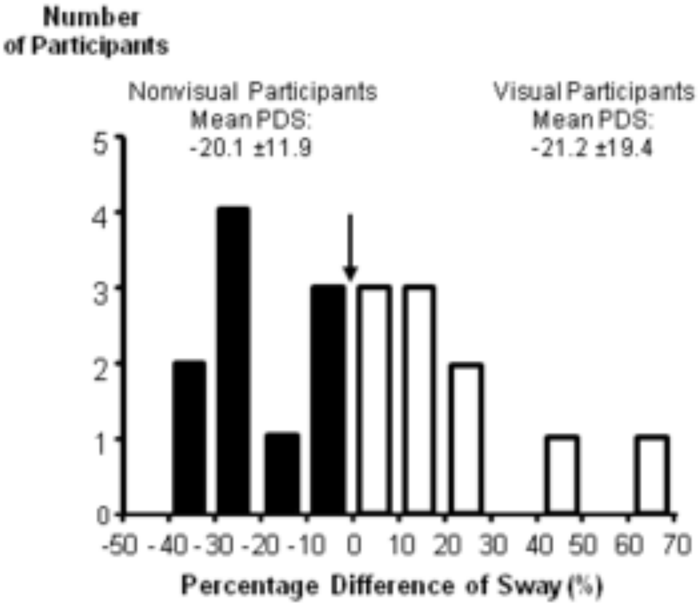
Number
of Participants
Nonvisual Participants
Mean PDS:
-20.1 ±11.9
Visual Participants
Mean PDS:
-21.2 ±19.4
5
4
3
2
1
0
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
Percentage Difference of Sway (%)

Figure 5

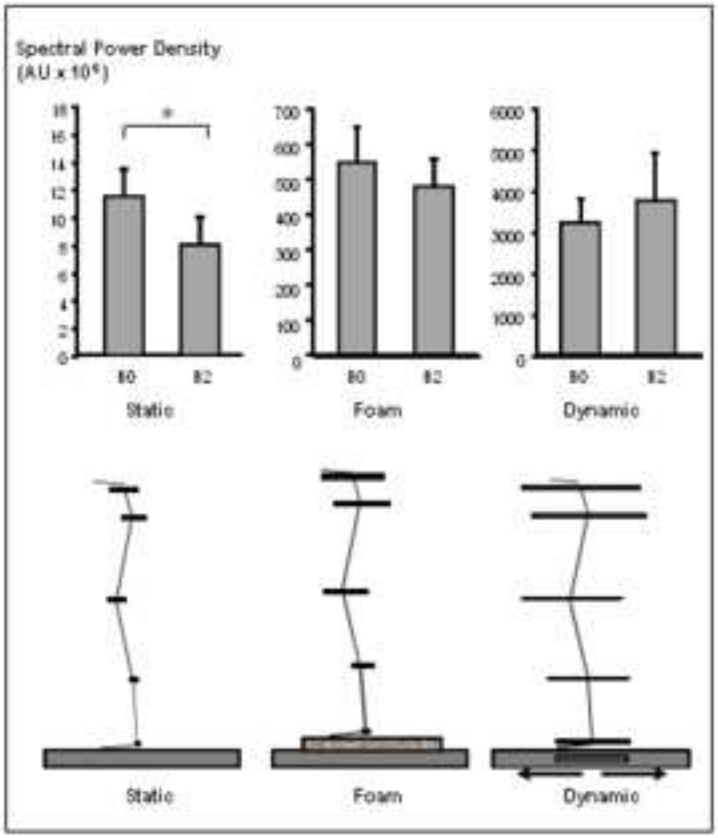
Spectral Power Density
(AU x 10^6)
*
18
16
14
12
10
8
6
4
2
0
B0
B2
Static
700
600
500
400
300
200
100
0
B0
B2
Foam
6000
5000
4000
3000
2000
1000
0
B0
B2
Dynamic
Static
Foam
Dynamic

Figure 6