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RESEARCH ARTICLE

Vibratory noise to the fingertip enhances balance improvement associated with light touch

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Abstract Light touch of a fingertip on an external stable surface greatly improves the postural stability of standing subjects. The hypothesis of the present work was that a vibrating surface could increase the effectiveness of fingertip signaling to the central nervous system (e.g., by a stochastic resonance mechanism) and hence improve postural stability beyond that achieved by light touch. Subjects stood quietly over a force plate while touching with their right index fingertip a surface that could be either quiescent or randomly vibrated at two low-level noise intensities. The vibratory noise of the contact surface caused a significant decrease in postural sway, as assessed by center of pressure measures in both time and frequency domains. Complementary experiments were designed to test whether postural control improvements were associated with a stochastic resonance mechanism or whether attentional mechanisms could be contributing. A full curve relating body sway parameters and different levels of vibratory noise resulted in a U-like function, suggesting that the improvement in sway relied on a stochastic resonance mechanism. Additionally, no decrease in postural sway was observed when the vibrating contact surface was attached to the subject's body, suggesting that no attentional mechanisms were involved. These results indicate that sensory cues obtained from the fingertip need not necessarily be associated with static contact surfaces to cause improvement in postural stability. A low-level noisy vibration applied to the contact surface could lead to a better performance of the postural control system.

Keywords Sway · Stochastic resonance · Vibration · Postural control · Somatosensation · Posture stabilization

Abbreviations

ANOVA	Analysis of variance
AP	Anterior–posterior
BS	Best stimulation
COP	Center of pressure
COPap	COP in the anterior–posterior axis
COPml	COP in the medio-lateral axis
g	Gravity of Earth
HF	High frequencies
LF	Low frequencies
LT	Light touch
ML	Medio-lateral
PSD	Power spectral density
QS	Quiet standing
RMS	Root mean square
RMSap	COPap RMS
RMSml	COPml RMS
SD	Standard deviation
SR	Stochastic resonance
VMap	COPap velocity
VMml	COPml velocity
VS1	Vibratory stimulation 1, at intensity 0.4 *g*
VS2	Vibratory stimulation 2, at intensity 0.8 *g*

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Introduction

Several studies have investigated the relationship between postural sway and contact forces at different body parts

(Holden et al. 1994; Jeka and Lackner 1994; Krishnamoorthy et al. 2002; Rogers et al. 2001). Particularly, when a subject's index finger touched a rigid static surface (with applied force <1 N, thus providing no mechanical support), light touch cue improved postural stability during quiet tandem stance (Jeka and Lackner 1994, 1995) and single-limb standing (Holden et al. 1994) while also decreasing postural sway induced by predictive and reactive balance perturbations (Johannsen et al. 2007). These findings suggest that sensory inflow from the fingertip can provide orientation information that enhances control of upright stance. However, if the same experiment was repeated with a sinusoidally moving contact surface (at 0.1–0.5 Hz), a temporal relationship between body sway and the contact surface movement occurred, causing an increased amplitude of postural sway (Jeka et al. 1997).

In the present experiments, we investigated whether a further increase in postural steadiness (compared to that observed when subjects touched a stationary surface) could be achieved by applying a low-level mechanical noise (i.e., vibratory noise) to the fingertip's contact surface. The hypothesis was that a stochastic resonance (SR) phenomenon could contribute to the stabilization of a standing subject touching a vibrating surface. The SR phenomenon, which has been described in very different settings, is associated with an improvement in performance of a given system in response to an appropriate level of noise (McDonnell and Abbott 2009; Moss et al. 2004; Wiesenfeld and Moss 1995). The improvements in the detection, transmission, and discrimination of signals by neurons and neuronal networks subjected to adequate noise levels are the embodiment of the SR phenomenon in the nervous system context (McDonnell and Abbott 2009; Moss et al. 2004).

In a simplified view of SR, noise, which is usually viewed as detrimental to signal detection and transmission, provides a suitable pedestal for enhancing the detection and transmission of an input stimulus (Priplata et al. 2002). For example, a low-level mechanical noise may cause small and random receptor potential fluctuations, which added to a normally subthreshold stimulus (e.g., mechanical tactile input) can make the membrane potential reach firing threshold and the stimulus to be detectable (Gravelle et al. 2002). However, this improvement in signal detection and transmission will occur only for a particular range of the input noise intensity. Too low noise levels will have no effect, while too high noise levels will worsen stimulus detection (Cordo et al. 1996).

Previous work in the literature has shown examples of SR as an aid to reduce postural sway. Electrical or mechanical noise stimulation applied to a subject's leg or feet has been found to improve postural stability in different populations, such as healthy young and older subjects (Priplata et al. 2002, 2003), patients with diabetic neuropathy and stroke survivors (Priplata et al. 2006), and subjects with functional ankle instability (Ross 2007).

Manjarrez et al. (2002) showed that the signal-to-noise ratio of the somatosensory cortical activity elicited by mechanical tactile stimuli (local indentations applied to glabrous skin of the middle fingertip) was optimized by the addition of a particular level of vibratory noise. This evidenced an SR phenomenon in the sensory system comprising the flow of tactile information from the mechanoreceptors up to the cerebral cortex. However, an important question, which is addressed in the present paper, is whether the increased sensory inflow from the fingertip to the cortex caused by vibratory noise can indeed be used with advantage by the central nervous system to improve postural stability.

In the present investigation, we hypothesized that the reduced postural sway observed when a subject's index finger touched a stationary surface (Jeka and Lackner 1994) could be further reduced by applying a low-level mechanical noise to the contact surface. In this sense, noise vibration applied to the contact surface would provide enhanced orientation information (by improving neural communication) and hence would further reduce postural sway when compared to the stationary light touch condition. Therefore, the basic experimental paradigm consisted of analyzing postural sway parameters during light touch on a static and on a vibrating contact surface.

The vibratory noise levels utilized in the experiments were of low intensity, but above sensory threshold. Therefore, special care had to be taken to discard the possibility that the vibration applied to the contact surface changed the subject's attentional state thereby improving postural control. For this purpose, the experiments were also conducted with the contact surface attached to the subject's body (sway-referencing). Sway-referencing of light touch provides the central nervous system with signals that are not helpful for improving the postural control system (Reginella et al. 1999). Therefore, if an improved postural control could be achieved by an increase in attention caused by the vibration, a reduced sway would also be expected in the sway-referenced vibrating contact surface paradigm.

Methods

Participants

Ten subjects (6 males, 4 females, 28.1 ± 5.3 (SD) age) volunteered to participate in this study. All subjects were healthy and physically active, with no known musculoskeletal injuries or neurological disorders that might have affected their ability to maintain balance. All were right-handed. The experiments had approval of the local ethics committee and were conducted in accordance with the Declaration of Helsinki. Each subject signed an informed consent document.

Touching apparatus

The subject's right index fingertip was stimulated mechanically by means of a LW-126-13 vibration system (Labworks, USA), consisting of a power amplifier and a shaker (cylindrical body, with diameter 10.5 cm and length 13.5 cm). The shaker was fixed over a tripod, and a flat metal plate was attached to the movable part of the shaker, in such a way that vibratory oscillations could be generated either vertically or horizontally (the latter was along the index finger's axis, see Fig. 1). The metal plate was covered with a layer of fine grit sandpaper, providing a textured contact surface for the index finger. The height, position, and orientation of the touch surface could be adjusted to accommodate for the differences in the subjects' heights. The subject's right arm was kept at the side of the body, and the forearm was kept raised so that the touch bar was approximately at the subject's navel level. A LabView system (National Instruments, USA) was utilized to generate 120 s duration gaussian white noise signals, which were delivered to the input of the shaker's power amplifier in order to obtain the desired mechanical stimulation. An ADXL78 accelerometer (Analog Devices, USA) was attached to the movable part of the shaker in order to monitor the parameters of the mechanical stimuli (see Fig. 1, for a visualization of the vibration noise acceleration amplitude distribution and spectrum). In this paper, acceleration units are given as multiples of the gravity of Earth, indicated as g (about 9.81 m/s^2). For example, 0.4 g indicates an acceleration equal to 0.4 times the gravity of Earth. In addition, a strain gauge force transducer (Transtec NA330, Brazil) was attached beneath the shaker to measure the vertical forces applied by the finger. All data acquisition and analysis employed customized programs written in LabView (National Instruments, USA) and Matlab R2007 (Mathworks, Inc.).

Experiment 1

Procedure

The experimental subject was asked to select a comfortable position and stand barefoot as quietly as possible over a force plate (OR6-7-1000, AMTI, Watertown, USA), with feet apart at approximately shoulder width. The force plate was rigidly fixed to the ground floor while the tripod that held the touching apparatus rested upon an elevated floor (this avoided vibration to spread from the shaker to the force plate and the subject's foot soles). The subject's right index fingertip touched a flat metallic surface mounted on the shaker. All experiments were performed with closed eyes and with auditory masking to avoid any influence of the low intensity but audible noise emanating from the shaker. The subjects had no previous knowledge about the experimental hypotheses, and they were not given feedback about their postural performance.

The position of the subject's feet on the platform was marked with adhesive tape to ensure that the same position relative to the touching apparatus was repeated on each trial. The touch surface was either stationary or subjected to a vibratory noise of two different intensities and applied either vertically or horizontally (perpendicular or parallel to the finger's axis). The intensities, characterized by the root mean square values (RMS) of the acceleration random processes, were 0.4 and 0.8 g (g is the acceleration of gravity), measured while the subjects were touching the surface. The three stimulation conditions were as follows: (1) light touch (LT, i.e. stationary touch surface), (2) vibratory stimulation 1 (VS1, i.e. touch bar randomly vibrating with an intensity level set at an RMS value of 0.4 g), and (3) vibratory stimulation 2 (VS2, at an RMS value of 0.8 g). These vibratory stimulation intensity levels were chosen based on pilot studies indicating that they were usually within an intensity range that improved balance control over that achieved by LT (see also Experiment 2).

In order to estimate the RMS values of the contact surface random displacements (due to the vibratory noise), an Optotrak 3020 motion tracking system (Northern Digital, Inc.) was used, with an infrared emitter placed at the tip of the shaker. Image data were acquired at 1,500 Hz while a subject was touching the contact surface. RMS displacement values about 0.050 and 0.100 mm corresponded to the RMS acceleration values of 0.4 and 0.8 g, respectively. The displacement signal spectrum was a monotonically decreasing function with −3 and −20 dB frequency values at 10 and 75 Hz, respectively.[1]

At the beginning of each experimental session, the subject was asked to look at an oscilloscope trace that displayed the vertical force signal generated by their

[1] It has been previously demonstrated that optimal configurations of the motion tracking system are able to produce measurements with precision and repeatability less than 1 μm (Schmidt et al. 2009). Nevertheless, additional measurements were performed (all with the subject touching the surface) with higher intensities of vibratory noise, so that measured displacements were within the resolution of the tracking system warranted by the manufacturer (100 μm). A linear relationship between the intensity of the noise signals delivered to the input of the shaker and both displacements and acceleration measures was observed. This confirmed that the estimation of RMS displacement values about 0.050 and 0.100 mm (corresponding to the 0.4 and 0.8 g noise RMS acceleration values, respectively) was indeed reliable.

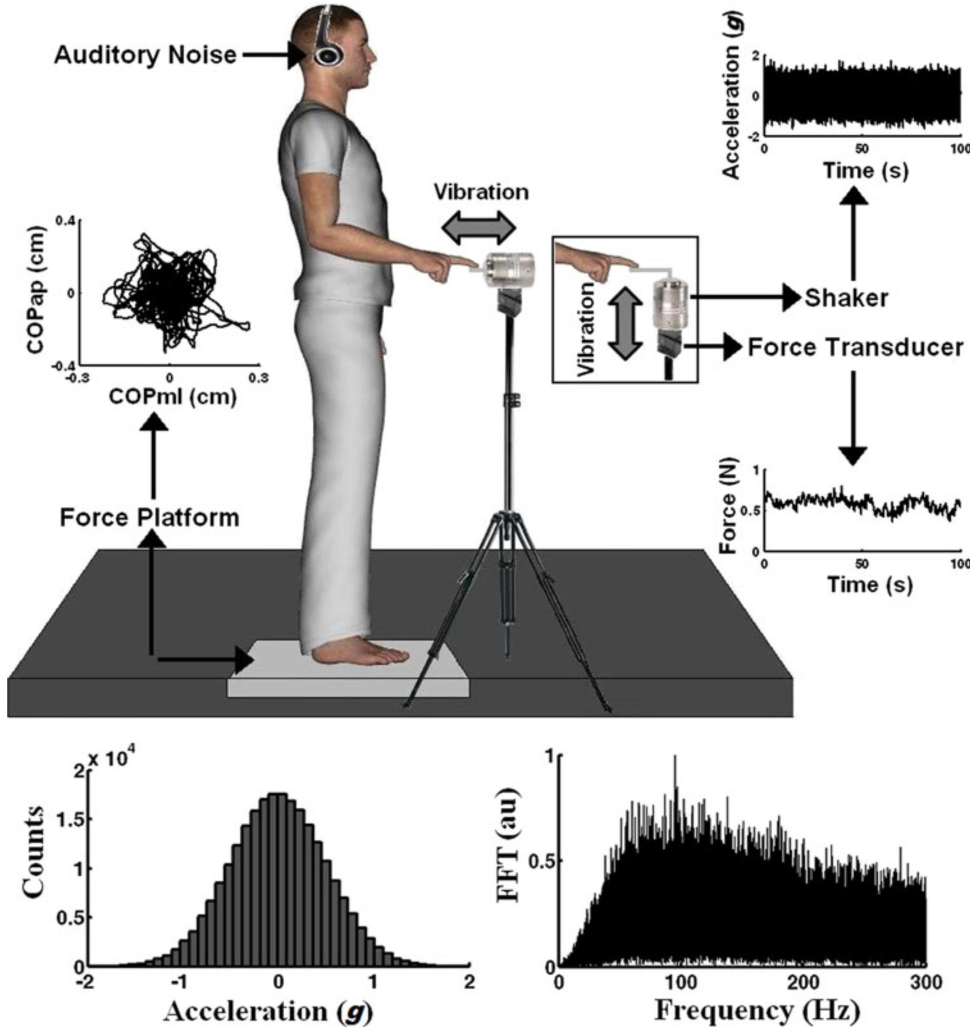

Fig. 1 Experimental setup utilized in experiments 1 and 2. Subjects stood quietly over the force plate while touching the vibratory apparatus with their right index fingertip. Vibratory noise stimuli were applied either horizontally or vertically to the fingertip (*inset*). During all trials, subjects wore a headphone that played an auditory masking noise. Three types of signals can be seen in the figure: one acquired from the force transducer (indicating the vertical forces applied by the fingertip), an acceleration signal measured from the tip of the shaker, and the stabilogram (COPap × COPml as they vary with time). The two *graphs* at the *bottom* show the amplitude histogram and the absolute value of the FFT of the Gaussian vibration noise acceleration signal measured at the tip of the shaker

finger's touch. He/she was asked to apply less than 1 N of force, which was marked on the screen. After being able to stand quietly with a vertical fingertip force less than 1 N, one to two practice trials were performed before data collection started. In order to make sure that the fingertip vertical force was always under 1 N (thus providing no mechanical support), the force signal was monitored online by a customized software written in LabView. The force signal acquired during each trial was low-pass filtered (5-Hz cutoff) by a fourth-order Butterworth filter (this eliminated the movement artifacts due to reaction forces caused by the vibration of the shaker). If, at any time, more than 1 N was applied by the subject's finger, an alert sign appeared at the investigator's screen, and the trial was rejected and repeated. This, however, happened in less than 3% of the trials, measured forces being usually well below the 1 N threshold.

Each volunteer performed six trials, each lasting 120 s, for each of the three stimulation conditions (LT, VS1, and VS2, presented in a randomized order). The experiments were conducted in two different days, one for each of the vibratory stimuli (vertical and horizontal). Control trials with the stationary touch surface (LT) were performed in both experimental sessions. Additionally, 120 s of data were also acquired during upright quiet standing (QS condition, arms comfortably hanging by the side of the body). A resting period of ~120 s between trials was allowed to avoid fatigue (subject sat in a comfortable armchair placed next to the force plate). Each experimental session lasted approximately 2 h.

Center of pressure (COP) analysis

The forces and moments measured by the force plate were used to compute the two components of the center of pressure (COP): in the anterior–posterior axis (AP) and the medio-lateral axis (ML), indicated as COPap and COPml, respectively.

Before analysis, the COP data (acquired at 2 kHz) were low-pass filtered with a fourth-order Butterworth filter having an 8-Hz cutoff frequency. After filtering, the first 20 s of each trial were discarded to avoid adaptation transients, and the mean was subtracted from each time series. The root mean square (RMS) and mean velocity of the COP data were computed for each axis (i.e. AP and ML). The area of the stabilogram was estimated from the COP data by fitting an ellipse to the AP × ML COP data that encompasses 95% of the data (using the method proposed by Oliveira et al. (1996)). The COP velocity was calculated by dividing the total COP displacement (sum of the absolute values of the samples) by the total time interval.

The power spectral density (PSD) of the COP data (for both AP and ML axes) was estimated in each experimental condition. The average power spectrum obtained in each condition from all 10 subjects was calculated. The power spectral density was estimated by the Welch periodogram of the detrended data with 40,000 samples per periodogram, resulting in a resolution of 0.05 Hz. A Hann data-window was used with subtraction of the best linear regression and an overlap of 20,000 samples (50% overlap).

Statistical analysis

Time domain COP measures (RMS, area, and mean velocity) were computed for each trial, and the mean of six trials for each stimulation condition (LT, VS1, and VS2) was calculated for each subject.

Percentage differences in the COP measures were calculated between LT condition and vibratory stimulation conditions (VS1 and VS2) to determine the "best" stimulation (BS). For each subject, the values of the percentage improvements over the LT case of each of the 5 sway quantifiers (i.e., area, RMS, and mean velocities for AP and ML axes) were compared between the VS1 and VS2 (Table 1). The BS was defined as VS1 if at least 3 of the quantifiers were higher for VS1 (in percentage improvement) than for VS2, and vice versa.

Normality of the data was tested using the Kolmogorov–Smirnov method ($P < 0.05$). As the null hypothesis of Gaussian distribution was not rejected for all dependent variables, parametric tests were used for comparisons. A two-tailed paired t test was used to compare the BS and LT condition means for the population (α was set at $P < 0.05$). Effect size [ES, also known as "strength of association" (Tabachnick and Fidell 2007)] was calculated using Cohen's effect size index (Cohen 1988). ES was considered large if >0.14.

A two-tailed paired t test was also used to compare the areas under the PSD between conditions (LT vs. BS) at two frequency bands: ''low frequencies'' (LF, 0.05–0.5 Hz) and ''high frequencies'' (HF, 0.5–2.0 Hz). Within the adopted low frequency range, the COP power spectrum approximates that of the center of gravity (Benda et al. 1994). The upper limit of the high frequency range was chosen because 99% of the total power of the COP signal during quiet standing has been reported to be below 2 Hz (Mezzarane and Kohn 2008).

All the analyses were performed using the statistical package SPSS 15.0 for Windows (SPSS, Inc., Chicago, IL).

Experiment 2

One of the characteristics of stochastic resonance is that as the intensity of the input noise is increased, the performance of the system rapidly increases to a maximum level and then slowly drops off (Douglass et al. 1993; Hidaka et al. 2001). The improvement in performance is therefore greatest at some intermediate, optimum noise intensity (Gravelle et al. 2002).

Thus, the graph of the system output (response amplitude or signal-to-noise ratio) as a function of the input noise level would look like an inverted U function (Manjarrez et al. 2002). In terms of the experiments that are described here, a large range of noise intensities should be tested in order to determine the "optimum noise intensity" of the vibratory stimulation for each subject. This would require long experimental sessions (which could lead to fatigue and/or discomfort) and/or fewer experimental trials (which could lead to less reliable measures). Therefore, only two vibratory noise levels (VS1 and VS2, chosen on the basis of pilot studies) were tested during Experiment 1, and the vibratory input intensity that produced the greatest improvement in postural stability was considered as the "best stimulation" (BS) for each subject.

In order to explore the full range of input noise vibration and its effects on postural sway stabilization, a long experiment was done on four subjects. This had the purpose of checking whether the putative mechanism behind the results could be stochastic resonance.

Thus, in Experiment 2, all procedures were identical to those previously described for Experiment 1, except that several intensity levels of the vibratory noise were tested: RMS = 0.2 g, RMS = 0.4 g, RMS = 0.6 g, RMS = 0.8 g, RMS = 1.2 g, and RMS = 1.6 g. The orientation of the vibration was only tested in the vertical axis.

A resting period of $\sim$3 min between trials was allowed, and a longer resting period ($\sim$5 min) was allowed every 5 trials. Each experimental session lasted approximately 5 h.

Data analysis involved normalization of both vibratory noise intensities and postural sway quantifiers, so that the data from all the subjects could be pooled together. Each vibratory noise level was divided by the noise intensity that caused the greatest reduction in the stabilogram area for each subject (the "optimum" noise level). In this way, the graphs of COP area values showed a minimum at abscissa

1 for all subjects. Postural sway quantifiers were expressed as a percentage of the corresponding average value obtained from the control (LT) condition.

A one-way ANOVA with planned comparisons (Sheskin 2007) (α set at $P < 0.05$) was used to compare the data for the LT condition with that for the optimum noise level. The general profile of the curve relating body sway parameters and different levels of vibratory noise was qualitatively analyzed on the basis of the 95% confidence interval computed from the LT condition.

Experiment 3

In Experiment 1, despite the randomized order of the three conditions (LT, VS1, and VS2), it cannot be assumed that the subjects were blind to the conditions, since the vibratory noise stimulations were above sensory threshold, albeit of low intensity.

Therefore, if the vibratory noise is shown to improve stance stability, it is necessary to rule out the possibility that this is due to an increase in attention caused by the fingertip vibration. The new experiments mimicked the previous ones, except that the vibratory device was fixed to the subject's body, i.e., it did not give a static ground reference, it was sway-referenced. Three subjects were tested with a lighter vibratory device (Bruel-Kjäer mini-shaker type 4810, Denmark) attached at waist level and slightly directed to the right side so that the fingertip contact would occur at approximately the same point in space as in Experiment 1. These subjects had shown in Experiment 1 a strong response to the vibratory noise stimulations (i.e. BS condition significantly enhanced postural stability when compared with the LT condition).

The touching apparatus was attached to the subject's body through a customized L-shaped wooden support fixed with a tight belt, so that the touching surface maintained the same height and distance in relation to the subject as during Experiment 1. Figure 6 (upper panel) depicts the 3 conditions tested in the sway-referenced experimental paradigm: (1) subject standing as quietly as possible over the force plate, with arms comfortably hanging at the sides, i.e. not touching the contact surface, (2) subject standing as quietly as possible over the force plate with the right index finger touching the non-vibrating surface, and (3) subject standing as quietly as possible over the force plate with the right index finger touching the vibratory surface.

The intensity level of the vibratory stimulus applied in these experiments was equal to that of each subject's BS previously found during Experiment 1 (VS1 or VS2), and the vibration orientation was only tested in the vertical axis. The experimental conditions were presented in a randomized order, and each subject completed 6 trials for each condition. These experiments were conducted at least 2 weeks after the subject's participation in Experiment 1.

Results

Experiment 1

When the subjects touched the quiescent surface (LT condition), there was a substantial reduction in postural sway in comparison with the quiet standing condition (QS condition), corroborating previous results from the literature (Clapp and Wing 1999). On average ($n = 7$), touching the stationary surface reduced COP area (Area) by 71.4%, COPap RMS (RMSap) by 61.7%, COPml RMS (RMSml) by 30.2%, COPap velocity (VMap) by 45.3%, and COPml velocity (VMml) by 31.1%. In addition, low frequency COP (AP and ML) spectral components were lower in LT when compared with QS.

The raw data from a single subject (Fig. 2) illustrate the differences found in the COP signals obtained in the different conditions.

Table 1 presents percentage differences between vibratory stimulation conditions (VS1 and VS2) and LT condition for each subject. For the first nine subjects, the best stimulation intensity was independent of the vibratory orientation (vertical or horizontal). VS1 was the best for 5 subjects and VS2 for the other 4 subjects. Only one subject (subject number 10, S10) showed different levels of preferred vibratory amplitudes for the vertical and horizontal orientation of the stimulus: the BS was VS1 for the vertical orientation and VS2 for the horizontal orientation.

When the vibratory stimuli were applied in the vertical orientation, BS condition significantly reduced Area ($t(9) = 3.11$, $P = 0.012$, ES = 0.51), RMSap ($t(9) = 4.10$, $P = 0.003$, ES = 0.65), and VMml ($t(9) = 2.76$, $P = 0.022$, ES = 0.45) in comparison to LT condition. The reduction observed in the variables RMSml and VMap did not reach statistical significance ($t(9) = 1.99$, $P = 0.077$, ES = 0.30 e $t(9) = 1.66$, $P = 0.130$, ES = 0.23, respectively). When the vibratory stimuli were applied in the horizontal orientation, BS condition significantly reduced Area ($t(9) = 3.84$, $P = 0.004$, ES = 0.62), RMSap ($t(9) = 4.03$, $P = 0.003$, ES = 0.64), and RMSml ($t(9) = 5.59$, $P < 0.001$, ES = 0.77), but the reduction observed in the variables VMap and VMml did not reach statistical significance ($t(9) = 1.17$, $P = 0.269$, ES = 0.13 e $t(9) = 1.45$, $P = 0.181$, ES = 0.18, respectively). Figure 3 shows individual and group data obtained for both vertical and horizontal vibratory stimuli during BS and LT conditions.

The area under the PSD of the COPap signal at low frequencies was significantly lower for BS condition when compared with LT condition ($t(9) = 2.27$, $P = 0.049$, ES = 0.36 and $t(9) = 2.62$, $P = 0.028$, ES = 0.43, for vertical and horizontal vibrations, respectively) (Fig. 4),

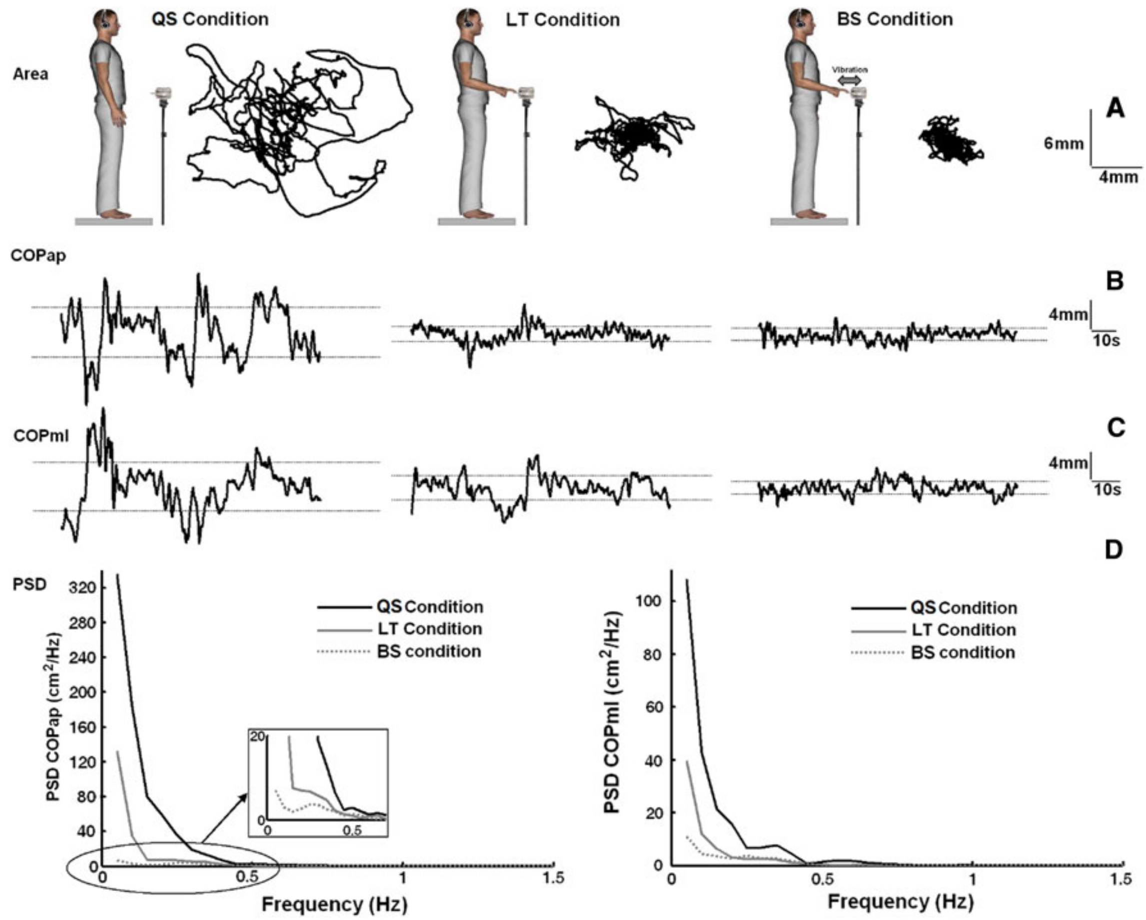

Fig. 2 Raw data from one subject during Experiment 1 (for vibratory noise applied horizontally). **a** Three experimental conditions (QS, LT, and BS) with the corresponding stabilograms calculated from COP data. **b** and **c** COP signals (for both AP and ML axes, COPap and COPml, respectively) recorded during 100 s. *Horizontal dashed lines* indicate ± RMS values about the mean position, allowing a qualitative assessment of postural sway decrease due to a tactile stimulus or a vibratory noise. **d** Corresponding power spectra estimated for the QS, LT, and BS conditions, for the AP (*left panel*) and ML (*right panel*) COP components. Note that the power at low frequencies decreased from QS to LT and also from LT to BS (*inset* in PSD COPap)

whereas no significant differences were found for COPml ($t(9) = 1.346$, $P = 0.211$, ES = 0.16 and $t(9) = 1.82$, $P = 0.101$, ES = 0.27, for vertical and horizontal vibrations, respectively). The reductions observed in the areas under the PSDs at high frequencies for COPap and COPml did not reach statistical significance regardless if the vibratory stimulus was applied horizontally or vertically. The specific values obtained from the statistical analysis were as follows: (1) $t(9) = 1.58$, $P = 0.147$, ES = 0.22 and $t(9) = 1.33$, $P = 0.214$, ES = 0.17, respectively for COPap and COPml when vertical vibration was applied and (2) $t(9) = 1.49$, $P = 0.170$, ES = 0.19 for COPap and $t(9) = 2.035$, $P = 0.072$, ES = 0.31, for COPml, both for horizontal vibrations. Additional statistical tests showed that significant differences ($P < 0.05$) between the power spectra are still obtained if the low frequency band is defined from 0.05 to 0.25 Hz or 0.05 to 0.4 Hz (instead of the range 0.05–0.5 Hz).

Experiment 2

Figure 5 (upper two rows of figures) shows the average time domain COP variables as a function of vibratory noise intensity obtained for the four subjects tested in Experiment 2. A reduction in the variables' values, i.e., an improvement in postural stability, was observed as the vibration intensity increased. After a minimum value was reached, the values of the COP variables increased (a worsening of postural stability) for higher vibration levels. Note that both noise intensity values and body sway quantifiers are normalized (see "Methods"). The optimum intensity of vibratory noise (corresponding to value 1 in the abscissa) significantly reduced Area ($F(1,158) = 7.14$, $P = 0.008$), RMSap ($F(1,158) = 14.24$, $P < 0.001$), RMSml ($F(1,158) = 4.66$, $P = 0.032$), VMap ($F(1,158) = 4.63$, $P = 0.033$), and VMml ($F(1,158) = 5.72$, $P = 0.018$) when compared to the control (LT) condition.

Table 1 Percentage difference of several sway measures between control condition (LT) and vibratory stimulation (RMS = 0.4 *g* and RMS = 0.8 *g*, respectively VS1 and VS2), for each subject tested in Experiment 1

Subject	Area		RMSap		RMSml		Vmap		Vmml	
	VS1	VS2	VS1	VS2	VS1	VS2	VS1	VS2	VS1	VS2
Vertical										
1	4.37	**24.49**	−7.35	**22.93**	8.70	**−5.33**	3.86	**6.89**	10.06	**13.02**
2	**5.90**	9.75	**12.13**	3.01	**6.28**	23.80	**3.74**	1.44	**5.57**	−2.35
3	**9.69**	−16.61	**5.64**	−7.04	**−1.63**	−18.04	**5.44**	4.46	**11.50**	0.30
4	**42.13**	9.44	**38.18**	0.28	**7.16**	10.09	**−18.42**	4.33	**−10.43**	−10.83
5	66.89	**71.44**	36.81	**42.48**	45.42	**47.23**	−1.06	**6.23**	29.38	**29.29**
6	−24.23	**14.71**	6.89	**31.55**	−50.24	**−12.58**	4.44	**1.971**	−4.27	**0.50**
7	61.48	**67.38**	33.50	**35.35**	−3.40	**46.30**	7.63	**12.45**	−9.09	**26.02**
8	**36.72**	2.22	**26.85**	−2.24	**17.51**	−5.97	**6.63**	7.47	**7.59**	−0.85
9	**14.58**	−44.84	**−3.53**	−31.25	**17.96**	−12.29	**7.79**	−4.45	**16.19**	0.34
10	**41.28**	15.26	**14.91**	3.88	**29.34**	9.65	**28.35**	26.12	**15.88**	15.51
Horizontal										
1	30.80	**46.36**	24.64	**26.85**	12.71	**27.54**	−10.76	**−3.84**	−12.53	**−2.63**
2	**26.63**	31.03	**18.01**	14.40	**13.99**	23.20	**1.57**	−2.6	**3.46**	0.54
3	**53.58**	20.69	**26.95**	17.04	**38.29**	7.63	**−8.29**	−7.13	**−1.33**	3.81
4	**45.08**	−2.27	**32.12**	−2.50	**18.78**	23.0	**2.71**	−23.70	**−3.79**	−24.91
5	43.62	**54.17**	35.94	**31.81**	29.10	**33.96**	19.84	**12.28**	27.06	**30.22**
6	−22.51	**−7.34**	−19.68	**−3.32**	3.46	**2.80**	−10.17	**−5.06**	−15.74	**−24.22**
7	49.10	**52.70**	22.76	**24.13**	35.64	**39.22**	11.69	**2.92**	22.94	**18.18**
8	**41.09**	−17.64	**11.40**	−26.52	**33.79**	2.82	**7.90**	−0.34	**9.45**	3.83
9	**39.34**	9.80	**17.05**	−11.30	**30.54**	22.75	**12.20**	−0.013	**35.55**	22.75
10	−22.07	**8.83**	−0.01	**4.34**	−8.11	**14.86**	14.71	**3.55**	9.13	**18.18**

Data corresponding to both horizontal and vertical vibratory stimuli are shown. Positive values indicate decrease in postural sway with vibratory stimulation while negative values indicate increase in postural sway. The numbers in bold indicate the best stimulation level (BS) used in the paired-samples *t*-test comparison (see "Methods" for criterion)

Figure 5 (third row of figures) shows average PSDs of the COP signals obtained for three conditions: LT, optimum noise level (minimized postural sway), and the highest noise level used for each subject. Spectra on the left correspond to COPap data and spectra on the right to COPml. It can be seen that the highest vibration intensity increased postural sway at all frequencies of the power spectrum. On the other hand, the optimum vibration level decreased the sway at all spectral frequencies when compared to LT.

Experiment 3

Figure 6 shows notched box plots representing the following COP parameters: Area, RMSap, RMSml, Vmap, and VMml. For the first three parameters, the median values increased gradually from conditions 1 to 2 and 2 to 3. The notches define the 95% confidence interval around the median; thus, groups that display overlapping notches cannot be considered different ($P < 0.05$). Therefore, when the vibration apparatus was attached to the subject's body, no differences in COP quantifiers were observed between the three conditions, particularly, the vibratory noise did not reduce postural sway parameters. PSDs computed from these trials strongly suggest that the vibration did not cause any improvement in postural stability in these subjects (those shown at the bottom right of Fig. 6 refer to COPap; similar results were obtained for COPml).

Discussion

SR has been demonstrated in a wide variety of physical and biological systems (Douglass et al. 1993; Gluckman et al. 1996; Morse and Evans 1996; Jaramillo and Wiesenfeld 1998; Stacey and Durand 2000; Hidaka et al. 2001), including ion channels (Bezrukov and Vodyanoy 1995), sensory systems (Collins et al. 1996, 2003; Cordo et al. 1996; Liu et al. 2002; Manjarrez et al. 2002), and the cat motor system (Martinez et al. 2007).

Manjarrez et al. (2002) showed that the signal-to-noise ratio of the somatosensory cortical activity elicited by

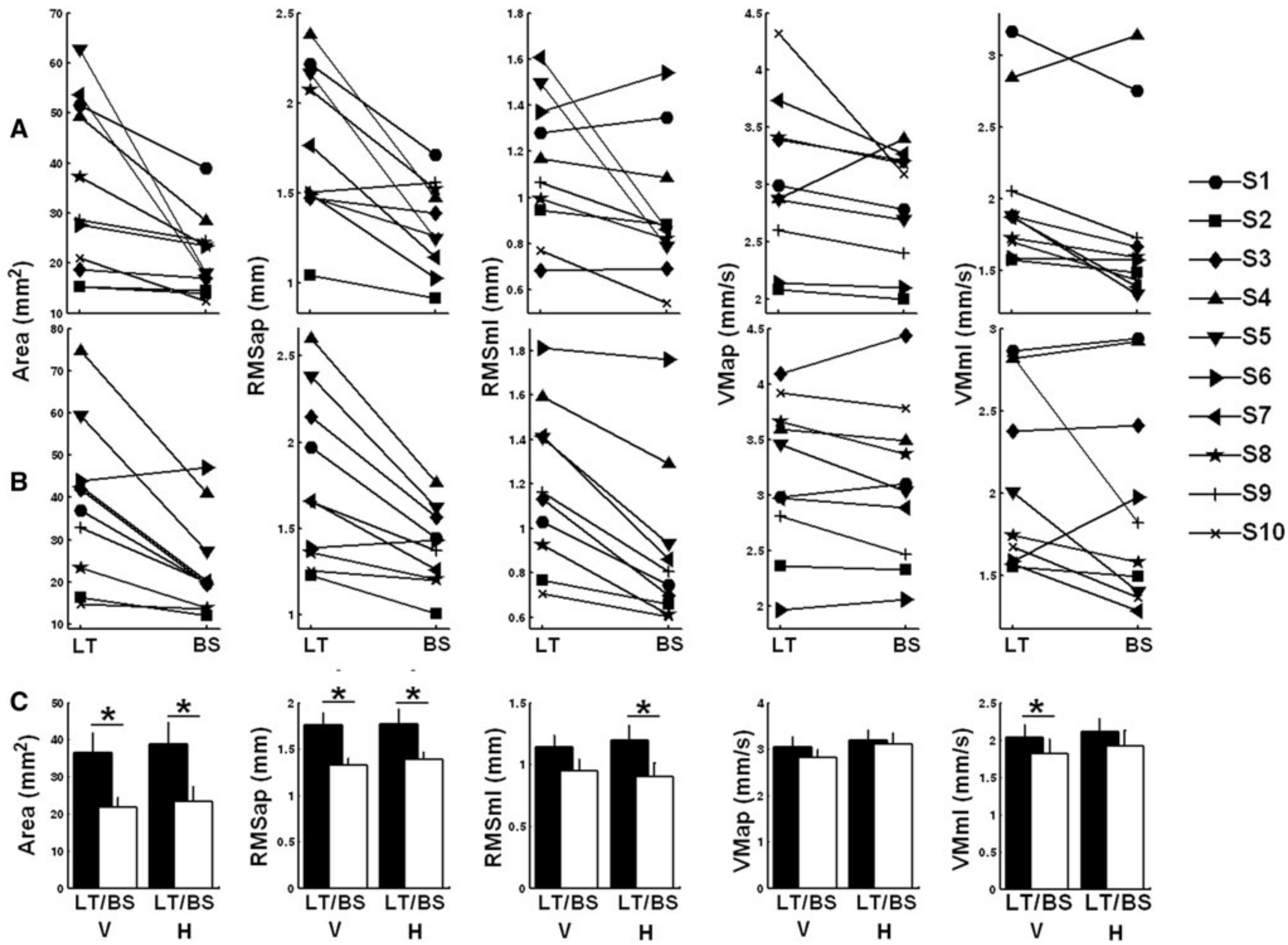

Fig. 3 COP measures computed from LT and BS conditions during Experiment 1. **a** From *left* to *right*, average ($n = 6$) Area, RMSap, RMSml, VMap, and VMml values calculated for individual subjects (S1–S10) when vibratory noise was applied vertically. **b** The same as in **a**, but for noise stimuli applied horizontally. **c** Average group data ($n = 10$) calculated for each variable during LT and BS conditions, for vibratory stimuli applied both in the vertical and horizontal axes (represented respectively by V and H at the bottom of the figure). *Asterisks* indicate significant differences ($P < 0.05$) between LT and BS conditions

mechanical tactile pulses to a fingertip was optimized by the presence of a particular level of vibratory noise. The results that were presented in the previous section suggest that the motor system can indeed benefit from the SR in the somatosensory system, at least with respect to postural control.

The results showed that appropriate levels of vibratory noise applied to the fingertip's contact surface significantly reduced postural sway measures (for both AP and ML COP components) when compared to the condition in which the surface was stationary. In the present investigation, the improvement in postural steadiness during the BS condition when compared to LT condition showed large effect sizes. The COP power spectrum analyses (see Fig. 4 and numerical results given in the text of Results/Experiment 1) suggested that the center of gravity was better controlled during fingertip vibration because the low frequency ranges analyzed approximate the center of gravity spectrum (Benda et al. 1994; Caron et al. 1997; Gage et al. 2004). Higher frequency spectral components of the COP were statistically indistinguishable between the LT and BS conditions, which was consistent with the small differences found in COP velocity between the two conditions (Fig. 3c).

Light touch-induced postural sway stabilization need not be constrained to conditions in which the contact surface is stable. Lackner et al. (2001) have shown that contact of the index finger with flexible filaments is also able to provide significant attenuation of body sway, and Albertsen et al. (2010) have demonstrated that haptic supplementation is effective even when provided by an unstable stick support. The present investigation extends this knowledge by showing that an appropriate level of vibratory noise applied to the fingertip's contact surface further enhances balance improvement due to light touch.

The mechanism behind the improvement in postural stability shown here is probably associated with the phenomenon of SR, as a typical SR-like behavior was

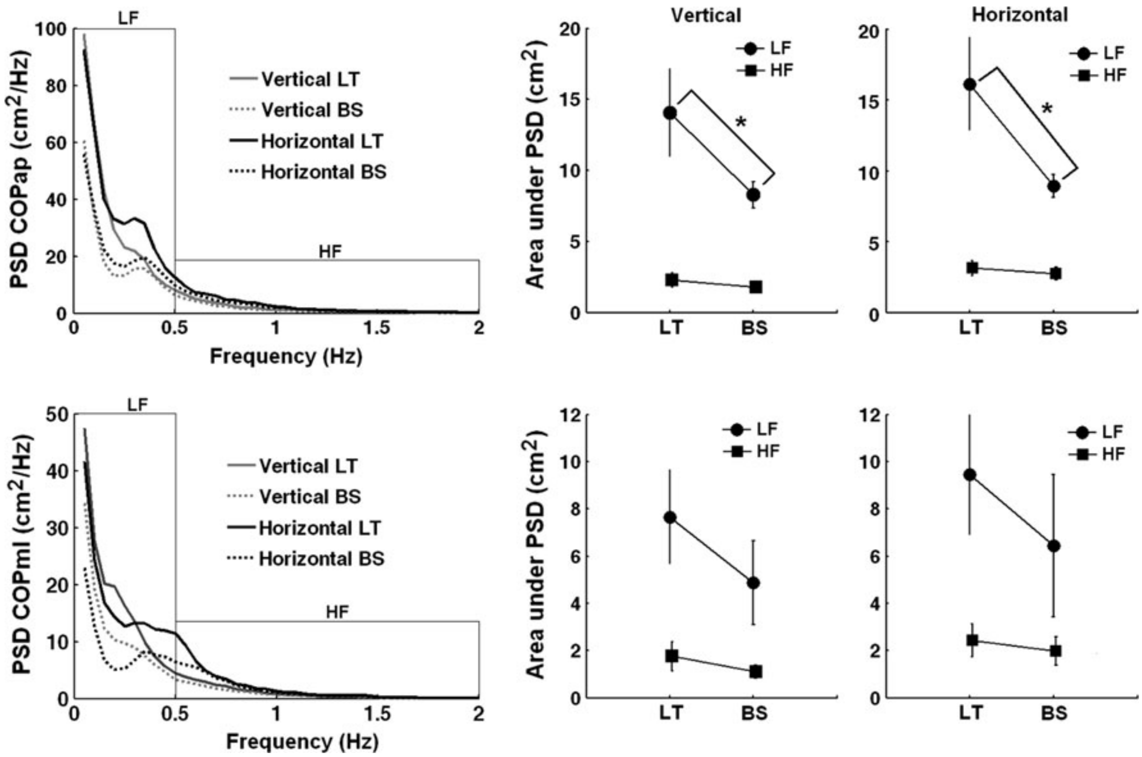

Fig. 4 Mean power spectra from 10 subjects estimated for LT and BS conditions (data for both vertical and horizontal vibrations are shown) with indications of two frequency bands of interest (low frequencies (LF) and high frequencies (HF)). At the right, the *figures* indicate corresponding area values for the LF and HF ranges. *Asterisks* indicate significant differences ($P < 0.05$) between LT and BS conditions

observed in Experiment 2. In SR, there are intermediate noise levels at which the system's performance is improved, while small noise levels cause little effect, and high noise levels worsen the performance (Cordo et al. 1996; Manjarrez et al. 2002; Martinez et al. 2007; Richardson et al. 1998). If the system's behavior is quantified by the response amplitude or the signal-to-noise ratio of the output, the SR phenomenon would be responsible for an inverted U-like function relating the system's behavior to the input noise intensity (Manjarrez et al. 2002; Martinez et al. 2007). In the present research, an improvement in system behavior corresponds to a decrease in the values of postural sway quantifiers. Thus, SR would be associated with a U-like shaped function between sway measures and noise level, i.e., vibratory noise intensity within a certain range would improve postural control (Fig. 5).

The classical SR theory establishes that the amplitude required to exceed the sensory threshold is reached by adding noise to the initially subthreshold stimulus (Moss et al. 2004; Ward et al. 2002; Faisal et al. 2008). However, this special case where noise allows a weak signal to become "detectable" often focuses on single neurons or receptors (McDonnell and Abbott 2009). The concept of beneficial noise does not need to be constrained to such conditions, in particular if a common signal is processed by a population of neurons (Stocks 2000), as happens in the present experimental paradigm. Light touch (a suprathreshold stimulus) would activate a fraction of a pool of mechanoreceptors, the other fraction being stimulated below threshold. The vibratory noise, within a certain range of intensities, would be able to activate an additional or more specialized set of mechanoreceptors, improving the representation of the input signals that reach the central nervous system.

If an attention/arousal mechanism would have had a significant effect in improving postural stability, this would also have occurred if the same vibration was applied to the fingertip but with the contact surface attached to the body. This was investigated in Experiment 3 in which a sway-referencing paradigm was utilized (the contact surface apparatus was attached to the subjects' body). No differences were found between the conditions of a non-vibrating contact surface and one with random low-amplitude displacements. This provided evidence that the results obtained in experiments 1 and 2 were not a simple consequence of an attention/arousal mechanism, but were very probably associated with an SR phenomenon.

Jeka et al. (1997) investigated postural control when the contact surface moved sinusoidally at constant frequencies (from 0.1 to 0.5 Hz; peak-to-peak displacement ~3.5

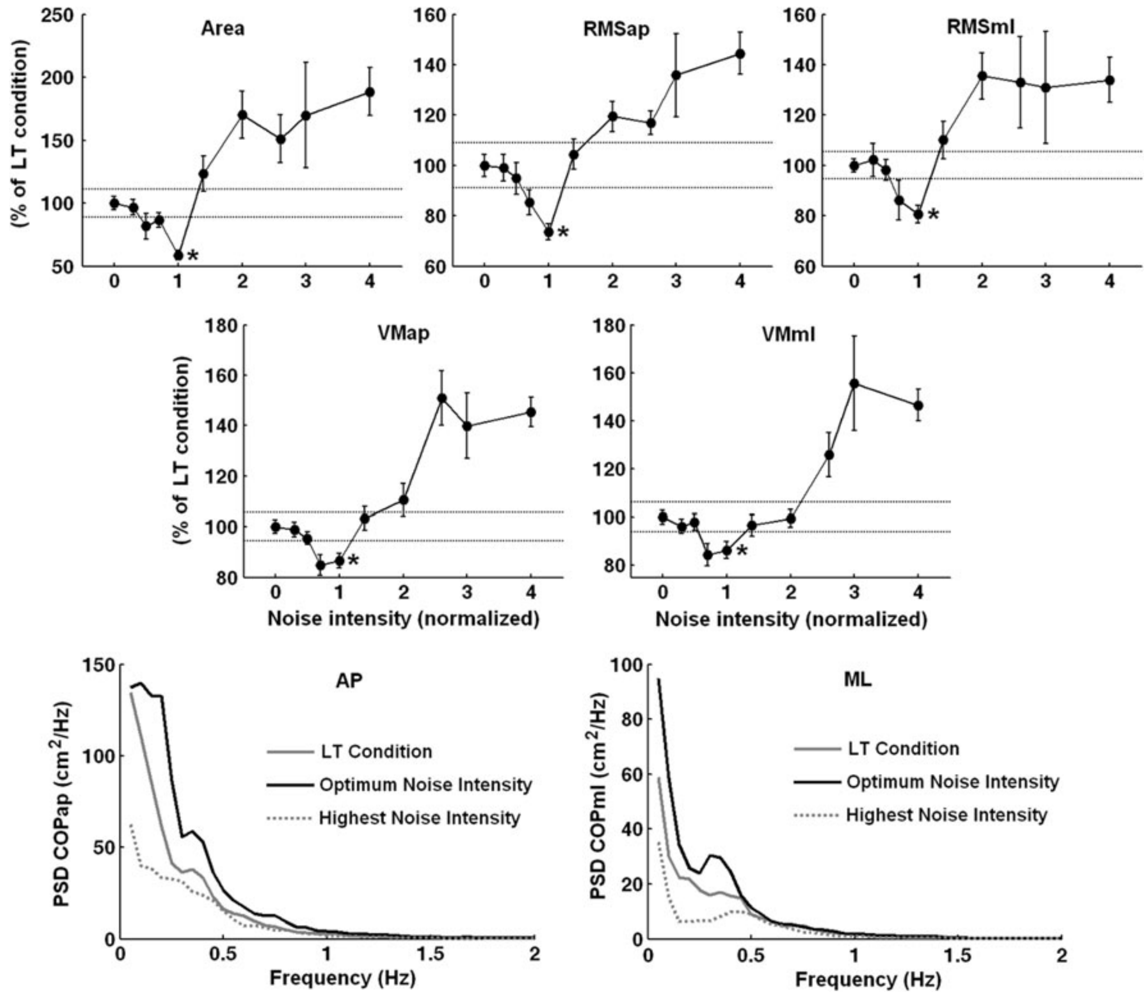

Fig. 5 Five average COP measures as a function of vibratory noise intensities (Experiment 2) are shown in the two upper panels based on data from four subjects. Each vibratory noise level is normalized with respect to the noise intensity that caused the greatest reduction in the stabilogram area for each subject (the "optimum" noise intensity). In this way, the graphs of COP area values show a minimum at abscissa 1 for all subjects. Postural sway quantifiers are expressed as a percentage of the corresponding average value obtained for the control (LT) condition. *Horizontal dashed lines* indicate the 95% confidence interval of the LT condition. *Asterisks* indicate significant differences ($P < 0.05$) between sway quantifiers computed at the "optimum" noise intensity and for the control (LT) condition. The lower panels show the mean power spectra of the COP signals from the four subjects. The highest vibration intensity caused an increased power at the whole range of postural sway frequencies when compared to the LT condition. On the other hand, the optimum vibration levels (normalized intensity noise = 1) decreased the postural sway power spectrum when compared to the LT condition (noise intensity = 0)

mm). Body sway increased in amplitude and showed a strong component at the frequency of the moving contact surface. In contrast, the present study showed reduced postural sway when the contact surface vibrated randomly. The differences between the present results and those from Jeka et al. (1997) may be attributed to the much higher movement frequencies and much lower amplitudes used in the present experiments (see "Methods").

The present results showed a clear acute improvement in postural stability, but the long-term effect of the vibratory noise is a question to be further investigated, as peripheral and central mechanisms may alter the effects seen here for larger duration vibratory stimulation. Another question to be investigated is whether applying horizontal and vertical vibratory oscillations simultaneously (and perhaps horizontal vibrations at both ML and AP axes besides the vertical orientation) may further increase postural stability when compared to uniaxial vibration.

The present results show that vibratory noise on the contact surface of the fingertip can lead to sway reductions in addition to those obtained by light touch in a normal bipedal stance. Whether the advantageous effects of vibratory noise may or may not be more pronounced in more challenging postural tasks (e.g. tandem-Romberg, single-limb standing, etc.) is an interesting question to be addressed in future research. It is interesting to point

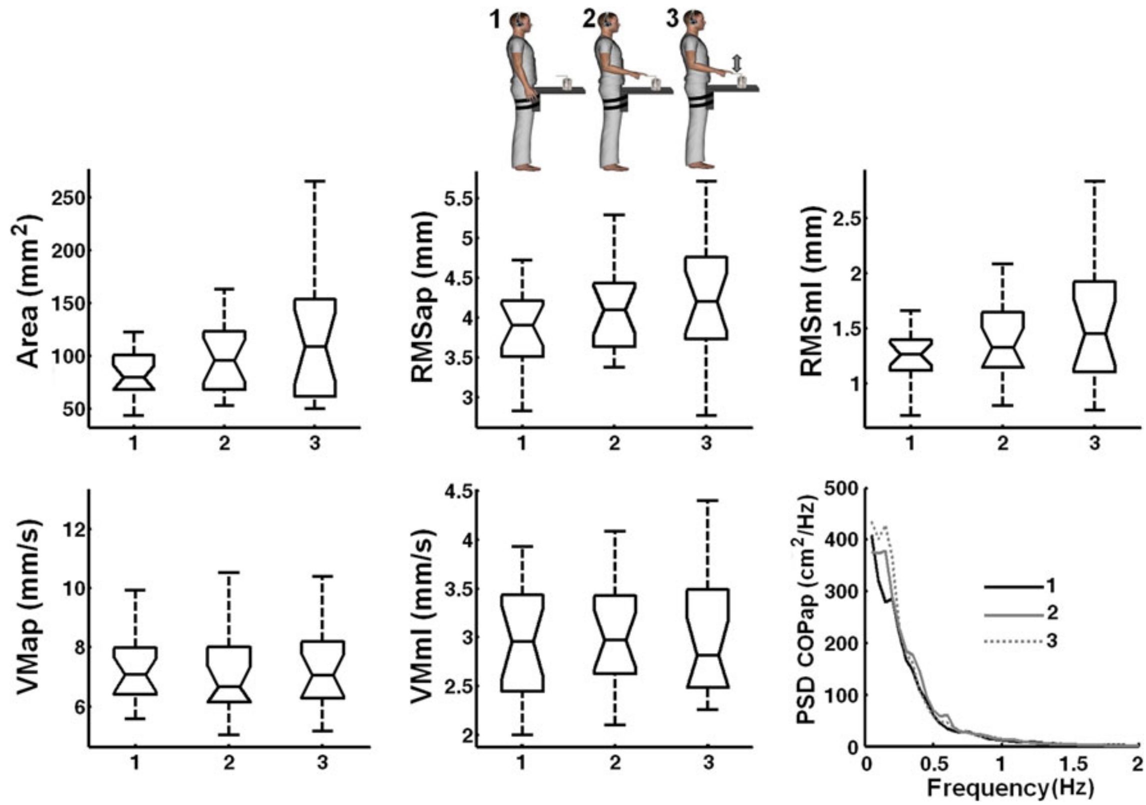

Fig. 6 COP measures obtained with the vibratory device fixed to the subject's body, i.e. sway-referenced paradigm (Experiment 3). The figure at the top illustrates the three experimental conditions: (1) subject standing quietly with arms hanging at the sides, (2) subject touching the static contact surface with the fingertip, and (3) subject touching the vibratory contact surface with the fingertip. Time domain measures are presented as notched *box plots* computed from three subjects. *Horizontal lines* of the *boxes* indicate the 25th, 50th, and 75th percentiles, and the whiskers extend from the *box* out to the most extreme data value. The notch defines the 95% confidence interval around the median (50th percentile); thus, groups that display overlapping notches cannot be considered different ($P < 0.05$). Note that no differences were observed between conditions. The *graph* at the *bottom right* shows three COPap average power spectra, each being an average computed from the three subjects during each of the three experimental conditions (1, 2, and 3 as shown at the *top* of the *figure*). Note that no improvements in postural stability were observed when a subject touched the contact surface (vibrating or non-vibrating) with the fingertip

out that the beneficial effects of light touch were initially shown in these less stable standing positions (Holden et al. 1994; Jeka and Lackner 1994) and later shown to occur also in the normal bipedal stance (Clapp and Wing 1999).

The results shown here suggest that the addition of vibratory noise to canes, walking sticks, handrails, etc., may be used as an aid to improve stabilization of normal bipedal stance (i.e. in daily life) in individuals with balance impairments.

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