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RESEARCH ARTICLE

Imperceptible electrical noise attenuates isometric plantar flexion force fluctuations with correlated reductions in postural sway

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Abstract Optimal levels of noise stimulation have been shown to enhance the detection and transmission of neural signals thereby improving the performance of sensory and motor systems. The first series of experiments in the present study aimed to investigate whether subsensory electrical noise stimulation applied over the triceps surae (TS) in seated subjects decreases torque variability during a force-matching task of isometric plantar flexion and whether the same electrical noise stimulation decreases postural sway during quiet stance. Correlation tests were applied to investigate whether the noise-induced postural sway decrease is linearly predicted by the noise-induced torque variability decrease. A second series of experiments was conducted to investigate whether there are differences in torque variability between conditions in which the subsensory electrical noise is applied only to the TS, only to the tibialis anterior (TA) and to both TS and TA, during the force-matching task with seated subjects. Noise stimulation applied over the TS muscles caused a significant reduction in force variability during the maintained isometric force paradigm and also decreased postural oscillations during quiet stance. Moreover, there was a significant correlation between the reduction in force fluctuation and the decrease in postural sway with the electrical noise stimulation. This last result indicates that changes in plantar flexion force variability in response to a given subsensory random stimulation of the TS may provide an estimate of the variations in postural sway caused by the same subsensory stimulation of the TS. We suggest that the decreases in force variability and postural sway found here are due to stochastic resonance that causes an improved transmission of proprioceptive information. In the second series of experiments, the reduction in force variability found when noise was applied to the TA muscle alone did not reach statistical significance, suggesting that TS proprioception gives a better feedback to reduce force fluctuation in isometric plantar flexion conditions.

Keywords Stochastic resonance · Postural control · Somatosensation · Posture stabilization · Force steadiness · Torque variability

Abbreviations

ANOVA	Analysis of variance
AP	Anterior–posterior
COP	Center of pressure
COPap	COP in the anterior–posterior axis
COPml	COP in the medio-lateral axis
ML	Medio-lateral
MVC	Maximal voluntary contraction
N	Newton(s)
OS	Optimal stimulation
RMS	Root-mean square
RMSap	COPap RMS
RMSml	COPml RMS
SD	Standard deviation
ST	Sensory threshold
TA	Tibialis anterior
TS	Triceps surae
VMap	COPap velocity
VMml	COPml velocity

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Introduction

In human movement or posture, motor output varies about the intended goal, limiting the precision and coordination of movements and the stability of posture. The sources of the variability may be sensory or motor, including in both cases not only the sensory receptors, axons and muscle fibers but also the central nervous system (Faisal et al. 2008).

It is well known that postural sway, gait and other motor activities are regulated by feedback signals from multiple sensory sources, e.g., mechanoreceptors associated with muscle, tendon, joint and skin. Electrical or mechanical noise stimulation applied to a subject's finger, leg or feet has been found to improve balance control in different populations, probably by increasing the sensitivity of sensory mechanoreceptors (Gravelle et al. 2002; Priplata et al. 2002, 2003, 2006; Ross 2007; Magalhaes and Kohn 2011; Kimura et al. 2011). The premise is that certain levels of noise can enhance the detection and transmission of sensory signals, by a mechanism known as stochastic resonance. For example, it has been shown that subsensory mechanical noise applied to the soles of the feet via vibrating insoles can be used to improve quiet-standing balance control in patients with diabetic neuropathy, patients after stroke and elderly subjects (Priplata et al. 2003, 2006). In other experiments, subsensory electrical noise stimulation applied to ankle muscles and ligaments has been shown to enhance postural steadiness of subjects with functional ankle instability (Ross 2007). It has been suggested that the improved detection of somatosensory signals by target receptors involved in muscle and joint sense provides enhanced information about body movement and position, thereby improving balance control.

The search for the optimal stimulation to improve postural control is a challenging task since the postural oscillations have to be recorded and quantified for each degree of freedom in stimulus choice: (1) intensity, (2) waveform and (3) places of application (foot soles, leg muscles, joints, etc.). The great number of trials needed would probably induce discomfort and/or fatigue. Therefore, a simpler experimental protocol would be extremely helpful for the optimal stimulation search.

Torque steadiness refers to the ability to perform voluntary muscle contractions with minimum fluctuations in torque while matching a given torque level (Enoka et al. 2003), either with visual feedback of the exerted torque or without it. In addition to its functional relevance, the maintenance of a constant force output is often an attractive and easily performed experimental task, and the variability in motor output, often measured in terms of force standard deviation (SD) or coefficient of variation, is frequently used as a metric of force control (Baweja et al. 2009, 2011).

Kouzaki and Shinohara (2010) have shown that plantar flexion torque fluctuations during low-intensity steady isometric contractions are significantly correlated with postural sway during quiet standing, by considering a sample that included data from both young and elderly adults together. Data obtained in our laboratory (Mello and Kohn 2009) showed that correlation between the levels of postural balance and the variability of matched torque levels during a maintained isometric force paradigm also occurs for a homogeneous class of subjects (i.e., young adults). Therefore, such a correlation suggests that the force-matching paradigm may provide a tool to ease the search of the optimum stimulation for postural sway reduction. If, hypothetically, noise-induced force variability decrease is linearly correlated with noise-induced postural sway decrease, then the search for optimal stimulation parameters to enhance postural control may rely on the much simpler experimental paradigm of isometric force control (which is performed in a more comfortable, seated position and requires shorter duration of experimental trials).

However, it is not known whether noise-based stimuli may attenuate force variability during a maintained isometric force paradigm and whether the ensued reductions in force fluctuations are correlated with enhanced balance control. These questions are addressed in the present paper, by exploring the effects of subsensory random electrical stimuli applied over the ankle muscles on plantar flexion force variability and on postural sway.

Muscle spindles play a key role in proprioception of movement by detecting changes in muscle length (Matthews 1981; Proske 2006). For instance, body sway during quiet standing is highly correlated with ankle joint rotation, and this is why the ankle muscles have the capability to provide sensory information necessary to maintain upright standing (Fitzpatrick et al. 1994; Gatev et al. 1999; Loram et al. 2005a). In this sense, the triceps surae (TS) muscles (i.e., soleus and the gastrocnemii) have traditionally been considered the main source of muscle proprioceptive information during quiet stance (Nashner 1976; Rothwell 1994). However, it has recently been suggested that this traditional assumption may not hold, since changes in muscle length of the TS muscles are almost entirely determined by fluctuations in muscle activity that are required for balance maintenance (Loram et al. 2005a, 2009). More specifically, generating sufficient tension in the TS muscles to maintain balance results in changes in muscle length which are not necessarily correlated with body sway, since the active fluctuations may mask the changes in muscle length which result from postural oscillations (Lakie et al. 2003; Loram et al. 2004, 2005a, b, 2007, 2009). Therefore, the active muscle modulation affects muscle length variations, and hence, modulation of muscle activity interferes with the proprioceptive role of the muscle. Consequently, length variations of a passive, un-modulated muscle may be more likely to reflect variations in joint rotation than muscle length variations that are affected by active modulation. For example, it has been shown that changes in muscle length of the tibialis anterior (TA) muscle [which is passive during standing (Mezzarane and Kohn 2009)] are better correlated with postural sway than length variations in the TS muscles (which are active during standing), suggesting that TA may be a better source of proprioceptive information than the active agonists (Di Giulio et al. 2009). Based on these last results, the present study also sought to compare the effects of noise-based stimulation applied over the TA and/or TS muscles on isometric plantar flexion torque fluctuations.

Therefore, the first set of objectives of this work was to investigate whether electrical noise stimulation applied over the TS muscles may decrease (1) plantar flexion torque fluctuations during steady isometric contractions and (2) postural oscillations during quiet stance. In addition, we sought to investigate whether there might be a correlation between a reduction in force fluctuation and a decrease in postural sway. If the traditionally accepted role of the TS muscles in providing proprioceptive information for balance control holds, then the hypothesis is that electrical noise applied to the TS muscles would provide enhanced proprioceptive information (by improving the detection and transmission of neural signals) and hence would reduce plantar flexion torque variability and postural sway when compared to the control (i.e., no noise) condition. The second objective was to investigate whether electrical noise stimulation applied over the TA muscle may decrease plantar flexion torque fluctuations during steady isometric contractions and to compare such reductions (if there are any) with those obtained by applying the noise stimulation over the TS muscles. If the suggested superiority of the TA proprioceptors (in comparison with the TS proprioceptors) in providing proprioceptive feedback for postural control forwarded by Di Giulio et al. (2009) also holds for isometric torque control, then the hypothesis is that the TA stimulation would result in a significantly larger decrease in torque variability than TS stimulation. Another question of interest was whether the stimulation applied to both anterior and posterior muscles is more effective than stimulation applied separately over a single muscle group. If both TS and TA provide proprioceptive information in force-matching tasks, then the working hypothesis is that the dual stimulation (TS and TA) would provide larger decreases in force variability than single muscle stimulation.

Methods

Experimental protocols

Two separate experimental protocols were designed and applied on different days. The first, Experiment 1, associated with the first set of objectives, consisted in applying imperceptible electrical noise to the TS muscles bilaterally in order to assess the effects of such stimulation on: (a) torque variability during a force-matching task of isometric plantar flexion (in seated subjects) and (b) postural sway during quiet stance.

The second, Experiment 2, associated with the second objective, consisted in applying imperceptible electrical noise separately over either the TA or TS muscle and simultaneously over both muscles in order to assess the effects of such stimuli on torque variability during an ipsilateral force-matching task of isometric plantar flexion (in seated subjects).

Participants

Eleven subjects [9 men, 2 women; 29.7 ± 5.8 years (mean $\pm$ SD)] volunteered to participate in this study. All subjects were healthy and physically active, with no history of musculoskeletal injuries or neurological disorders. All of them were right-footed. 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.

Electrical noise stimulation

A STIMISOL constant-voltage stimulator (BIOPAC Systems, Inc.) was driven by a computer that controlled the delivery of the electrical noise stimulation. A LabView system (National Instruments, USA) was utilized to generate noise signals (white noise filtered by a band-pass filter with cutoff frequencies at 5 and 2,000 Hz) with 50-s duration, which were delivered to the input of the STIMSOL in order to obtain the desired electrical current stimulation. Subsensory, low-intensity levels of electrical noise were applied in this study, and hence, no electrically induced muscle contractions occurred.

General procedures

The procedures described in this section pertain to methodological issues utilized in the force-matching tasks, which were conducted at the beginning of both Experiments 1 and 2 (subjects performed steady isometric plantar flexion contractions, in a seated position). As commented before, Experiment 1 also involved postural tasks during quiet stance, which will be described separately in a section pertaining to Experiment 1, as a particularity of that protocol.

Experimental setup

Subjects were seated comfortably on a customized chair, with armrest and headrest, designed for measuring ankle torque during isolated isometric plantar flexion contraction. The ankle of the right leg was maintained at 90°, while the knee was fully extended (180°) and the hip was at approximately 120°. The right foot was tightly fixed to a rigid metal pedal so that its axis of rotation was aligned with the medial malleolus. A strain gauge force transducer (Transtec N320, Brazil) was attached to the pedal to which the right foot was fastened.

Maximal voluntary contraction (MVC) measurement

At the beginning of the session, each subject's maximal voluntary force during plantar flexion was determined. Subjects were asked to perform three maximal voluntary contractions (MVCs) of the TS. MVC trials lasted 3–4 s each and had verbal encouragement and visual feedback of the exerted force, with 2-min rest between each trial. The maximum force value achieved across the three trials was taken as the MVC force value. All measurements in this paper are expressed as a percentage of the MVC (and hence we use the terms torque and force interchangeably).

Force-matching task

A custom-written program in LabView (National Instruments, USA) provided the visual feedback of the exerted force on an LCD monitor. The gain of the visual feedback remained constant for all subjects and conditions, because the reference signals in the computer monitor were always shown with the same calibration of *N*/division. The target torque was provided as a green horizontal line in the middle of the monitor and the force exerted by the subjects as a yellow line progressing with time from left to right. Subjects were instructed to maintain their force on the target as accurately and as consistently as possible for 50 s. The paradigm consisted of an initial 18-s interval during which the subjects visualized the output torque followed by a second interval of 32 s without visual feedback of the exerted torque (subjects were instructed to close their eyes at the 18th s, and the monitor stopped providing the visual feedback at the 20th s) (see Fig. 1 for examples). For the present study, we chose 10% of the subjects' MVC force as the target force because this value corresponds approximately to the plantar flexion torque exerted during quiet standing (Masani et al. 2008; Mello and Kohn 2009).

Only the segments of force signals acquired during eyes closed were analyzed. The rationale is that the elimination of the visual information challenges the neuromuscular system and accentuates the need for other sensorial information, increasing a possible effect of the electrical noise, if there is any (note that postural tasks were also performed with eyes closed).

The force-matching task began after a rest period of approximately 10 min from completion of the MVC measurements. A resting period of 1 min was allowed between the trials. Subjects had no previous knowledge about the experimental hypotheses, and they were not given feedback about their performance.

Experiment 1

In order to investigate the effects of electrical noise stimulation applied over the TS muscles, pairs of flexible silicon stimulating electrodes (each 10 cm long × 5 cm wide) were fixed over the subjects' calf muscles, bilaterally. The proximal electrode was positioned midway across the two portions of the gastrocnemius muscles, 10–15 cm distal to the popliteal fossa. The distal electrode was placed over the

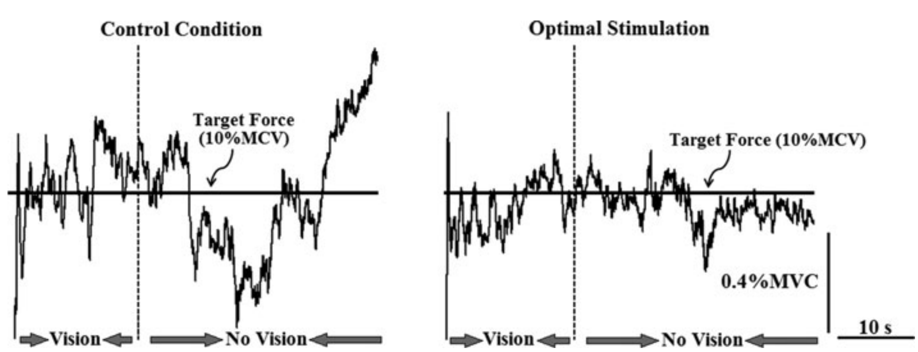

Fig. 1 Representative recordings of fluctuations in plantar flexion force from a subject during the force-matching task under control and optimal stimulation conditions (Experiment 1). The subject was instructed to exert a steady plantar flexion force against a rigid restraint and to match the horizontal target line (target force, set at 10%MVC) for 50 s. Visual feedback of the target line and exerted force was given to the subjects from 0 to 18 s (with vision period), whereas visual feedback was removed from 18 to 50 s (no vision period). The analysis of force variability was based on the no vision segments. The *left panel* represents the data recorded from a subject during control condition (with no stimulation), whereas the *right panel* represents the data recorded from the same subject during the optimal stimulation condition (with electrical noise applied bilaterally over the TS muscles). In this example, SD of force decreased from 0.21 to 0.06%MVC with optimal stimulation

soleus, just below the inferior margin of the two heads of the gastrocnemius muscles.

The sensory threshold (ST) of each subject was defined as the highest intensity (standard deviation, SD) of electrical noise stimulation that the subject was unable to perceive, and was individually determined before the experiment. In order to determine the ST, the intensity of electrical noise stimulation was gradually increased until the subject recognized it. The intensity was then slowly and carefully decreased until the subject was unable to perceive it.

The same LabView program that delivered the voltage noise signals to the input of the stimulator also controlled the experimental conditions that were presented during the force-matching task. Four experimental conditions were randomly presented, as follows: (1) no stimulation (i.e., control condition); (2) electrical noise stimulation with intensity set at 0.95 ST; (3) noise stimulation at 0.90 ST; and (4) noise stimulation at 0.85 ST. Each subject performed four trials, each lasting 50 s, for each of the four experimental conditions, with a 1-min resting period between trials.

After completion of the constant isometric force trials, subjects were liberated from the mechanical apparatus and were allowed to rest in a comfortable armchair (the stimulating electrodes were not removed) to wait for the beginning of the postural tests. In the meantime, the investigator quickly performed a preprocessing of the acquired data. A custom-written program in Matlab (Math Work Inc., USA) computed the SD of the force exerted in each experimental condition (with processing steps similar to those described in "Signal acquisition and processing"). The "optimal stimulation" condition (OS) was defined as the electrical noise stimulation intensity (0.95 ST, 0.90 ST or 0.85 ST) that produced the greatest reduction in force variability compared with the control condition. The OS observed for each subject was used as the electrical noise intensity level in the quiet standing task described below.

Quiet standing task

The subject was asked to select a comfortable position and stand barefoot as still as possible over a force plate (OR6-7-1000, AMTI, Watertown, USA), with feet apart at approximately shoulder width. The postural tasks were performed with eyes closed. The position of the subject's feet on the platform was marked with adhesive tape to ensure the same positioning across trials. Two experimental conditions were randomly presented: (1) control condition, in which no stimulation was delivered; and (2) stimulation condition, with electrical noise stimulation with intensity set at OS. Subjects performed five trials, each lasting 50 s, for each experimental condition. A resting period of $\sim$2 min between trials was allowed (subject sat in a comfortable armchair placed next to the force plate). The entire experimental session lasted approximately 3 h.

Experiment 2

Experiment 2 was designed to compare the effects of electrical noise stimulation on plantar flexion torque fluctuations between conditions that varied according to the site of application of the stimulation. All but 1 subject from Experiment 1 volunteered to participate. Therefore, 10 subjects participated in Experiment 2, and the procedures were conducted at least 24 h after Experiment 1.

Experimental conditions involved: (1) control condition, with no stimulation; (2) electrical noise applied to the TA muscle (TA condition); (3) electrical noise applied to the TS muscles (TS condition); and 4) electrical noise applied to both TA and TS muscles (TA + TS condition). In Experiment 2, all stimuli were applied unilaterally, on the subject's right leg, with the subject seated.

For the TS stimulation, the same electrodes and positioning procedures described in Experiment 1 were used. Smaller adhesive electrodes (5×5 cm) were positioned over the TA muscle belly. ST was determined using the same method described in Experiment 1, except for the fact that 3 different STs had to be determined (ST for TA + TS condition, ST for TS condition and ST for TA condition). The intensity level of the electrical noise stimuli applied in these experiments was equal to that of each subject's OS previously found during Experiment 1.

The four experimental conditions described above were randomly presented during the force-matching task. Each subject performed five trials, each lasting 50 s (18 s with and 32 s without visual feedback), for each experimental condition. The entire experimental session lasted approximately 3 h.

Signal acquisition and processing

Data acquisition

The signals from the strain gauge, the force plate and the noise signal delivered to the stimulator were acquired by an A/D board (PCI-6015, National Instruments, USA) at 4,000 samples/s. Data were analyzed off-line using custom-written programs in Matlab (Math Work Inc., USA).

Torque analysis

Thirty seconds of no-vision force segments were taken from the 19th to the 49th s of the 50-s signals (the initial and final portions of the periods with eyes closed were discarded to avoid transients due to subject's adaptation and signal filtering). Force signals were filtered with a fourth-order Butterworth filter having a 15-Hz cutoff frequency, and then, torque was computed from force. The mean and SD of torque (all expressed in % of MVC) were calculated. The SD of torque was quantified from the detrended signals because any drift from the targeted torque (especially during the absence of visual feedback condition) could influence the torque variability. This was achieved by removing the linear trend from the torque data.

Torque measures (mean and SD) were computed for each trial, and the mean value for each experimental condition was calculated for each subject.

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 4 kHz) were low-pass-filtered with a digital fourth-order Butterworth filter having an 8-Hz cutoff frequency, 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 (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.

COP measures were computed for each trial, and the mean of five trials for each experimental condition (control and noise stimulation at OS) was calculated for each subject.

Statistical analyses

All the analyses were performed using the statistical package SPSS 15.0 for Windows (SPSS, Inc., Chicago, Illinois), with significance level set at $P < 0.05$.

Experiment 1

Percentage differences in force SD were calculated between control condition (no stimulation) and electrical noise stimulation conditions (0.95 ST, 0.90 ST and 0.85 ST) to determine the OS condition. For each subject, the values of the percentage improvements in force variability over the control condition were compared between 0.95 ST, 0.90 ST and 0.85 ST (Table 1). The OS was defined as the electrical noise stimulation intensity that produced the greatest reduction in force variability compared with the control condition. This value of OS was then employed in the postural control experiments, so that COP measures (RMS, area and mean velocity) were obtained for the control and OS conditions.

Table 1 Percentage differences in force SD between control condition and noise stimulation conditions (0.95*ST, 0.90*ST and 0.85*ST), for each subject tested in Experiment 1

Subject	Condition		
	0.95*ST	0.90*ST	0.85*ST
1	15.0095	**32.9913**	17.5245
2	34.8937	32.6179	**35.2032**
3	23.3843	**40.3402**	27.8868
4	−15.2821	**5.5034**	−1.8570
5	10.8696	−4.9195	**18.6201**
6	3.1536	4.4936	**22.6665**
7	**16.4336**	−0.3746	−37.0634
8	−34.5234	**7.1445**	−5.5911
9	−49.2933	−18.9056	**8.9076**
10	−14.2885	**17.7068**	1.555
11	**15.9583**	10.4190	11.5642

Positive values indicate decrease in force SD with noise stimulation, while negative values indicate increase in force SD. The numbers in bold indicate the optimal stimulation condition (OS) used in the paired-samples *t* test comparison

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 OS and control conditions means for the population. Effect sizes (ES, also known as "strength of association") were calculated using partial eta squared indices (Tabachnick and Fidell 2007). ES was considered large if higher than 0.14.

Correlation analyses were performed to identify significant correlations between changes in force variability (expressed as percent reductions in force SD with noise stimulation) and changes in postural sway parameters (expressed as percent reductions in COP measures with noise stimulation).

Experiment 2

A one-way analysis of variance (ANOVA) with repeated measures and Bonferroni's post hoc tests were used to compare the data between the experimental conditions (control, TA condition, TS condition and TA + TS condition).

Results

Experiment 1

Torque analysis (mean and SD)

There were no significant differences between the mean forces exerted in all conditions: control (9.77 ± 0.64%MVC), 0.95 ST (9.69 ± 0.65%MVC), 0.90 ST (9.92 ± 0.44%MVC) and 0.85 ST (9.77 ± 0.61%MVC) (repeated measures ANOVA, $F(3,8) = 0.51$ $P = 0.681$).

As shown in Table 1, the stimulation intensity set at 0.95 ST was the optimal stimulation condition for 2 subjects, 0.90 ST for 5 subjects and 0.85 ST for the other 4 subjects.

There was no significant difference between the mean force exerted in control (9.77 ± 0.64%MVC) and in OS (9.71 ± 0.55%MVC) conditions ($t(10) = 0.54$, $P = 0.598$).

In Fig. 1, representative recordings of fluctuations in plantar flexion force show a clear reduction in force variability with optimal stimulation (right panel) compared to the control condition (left panel). Analysis performed on group data showed that OS condition significantly reduced plantar flexion torque variability ($t(10) = 4.32$, $P = 0.001$, ES = 0.65), as shown in Fig. 2.

COP analysis

Analyses performed on data from the experiments in quite stance (Fig. 3) showed that OS condition significantly reduced all COP measures in comparison with control condition. Table 2 shows the statistical output from the comparisons (*t* tests) between COP measures obtained in the control and in the optimal stimulation conditions.

Correlation analysis

For the study of the correlation between isometric force variability and postural sway parameters, we plotted the percent reductions in force SD against the percent reduction in COP measures achieved by electrical noise stimulation. A significant correlation was found between the percent reductions in force SD and COP Area and RMSap (Fig. 4). No significant correlations were found for RMSml, VMap and VMml. Figure 4 shows the best-line fits in the graphs relating percent reductions in force SD and percent reductions in COP measures that resulted in a significant correlation. The statistical output from the correlation tests performed between the reductions in COP measures and the reductions in force SD is shown in Table 2.

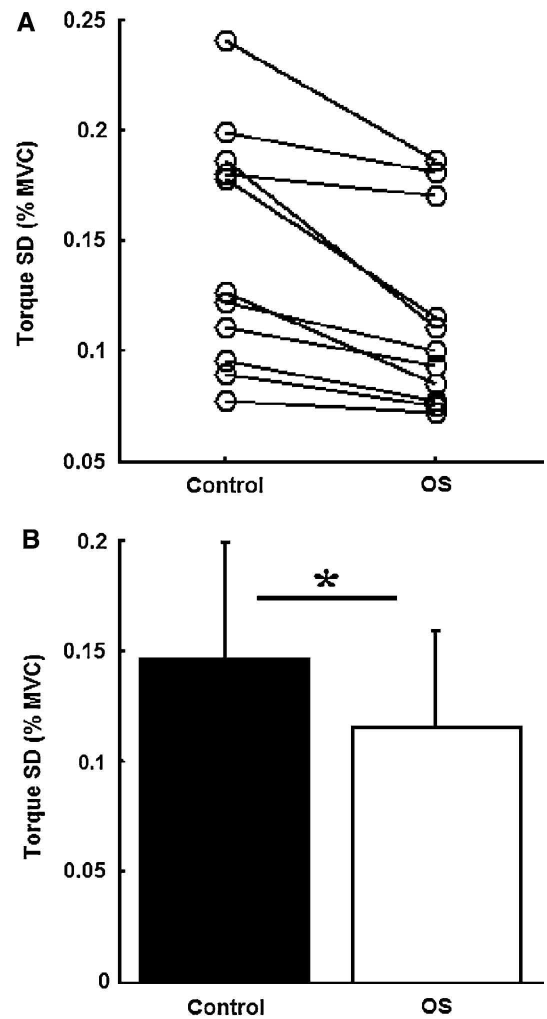

Fig. 2 Torque SDs computed from control and OS conditions during Experiment 1. **a** Average torque SD values calculated for individual subjects. **b** Average group data ($n = 11$) calculated during OS and control conditions. *Asterisks* (*) indicate significant differences ($P < 0.05$) between conditions

Experiment 2

In Experiment 2, there were no significant differences between the mean force exerted during the control condition (i.e., with no stimulation, mean force 9.71 ± 0.81%MVC) and during the conditions in which electrical stimulation was applied to the TA and TS muscles simultaneously (TA + TS condition, mean force 9.65 ± 0.69% MVC) and to the TS (TS condition, mean force 9.58 ± 0.82%MVC) and TA (TA condition, mean force 9.69 ± 0.86%MVC) separately (repeated measures ANOVA, $F(3,7) = 1.20$, $P = 0.377$).

Figure 5 shows individual (a) and group data (b) of plantar flexion force SD obtained during control, TA + TS, TS and TA conditions. Repeated measures ANOVA detected

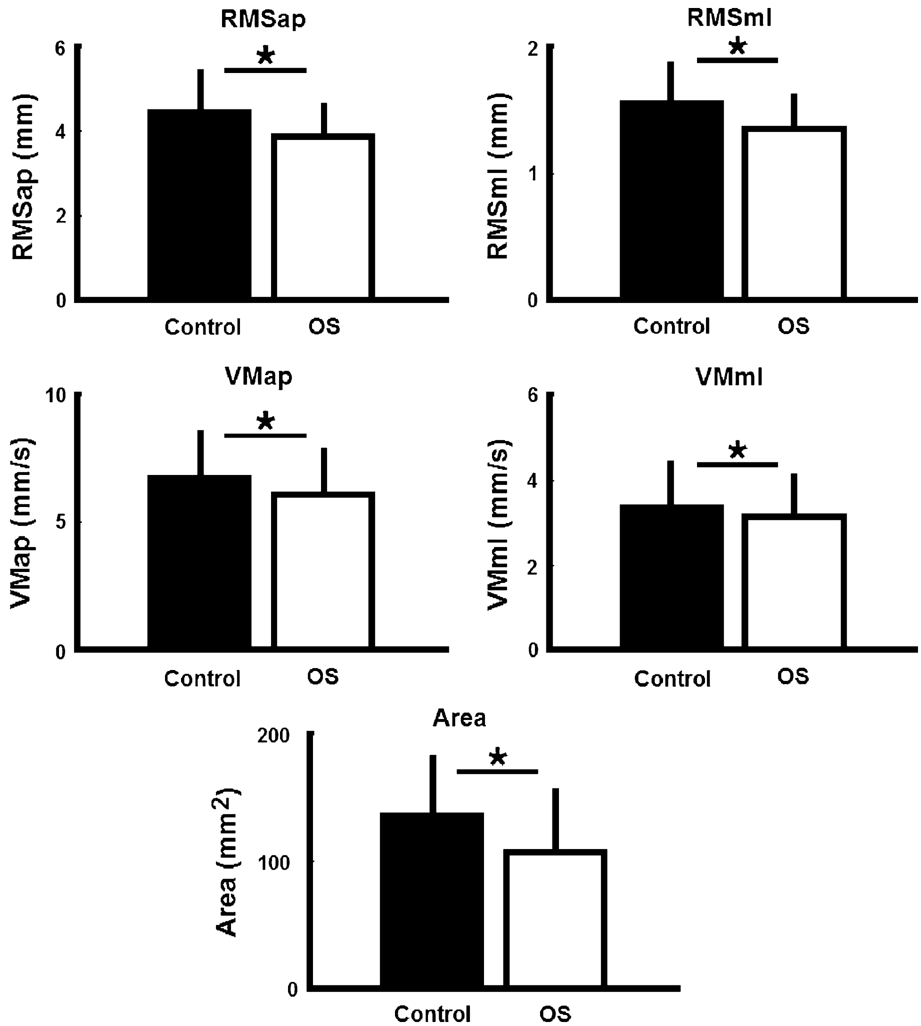

Fig. 3 COP measures computed from OS and control conditions during Experiment 1. Average group data ($n = 11$) calculated for RMSap, RMSml, VMap, VMml and Area, as indicated above each graph. *Asterisks* (*) indicate significant differences ($P < 0.05$) between OS and control conditions

Table 2 Results of *t* test and correlation analyses

COP measure	Comparison (control vs. OS)			Correlation (COP reduction vs. force SD reduction)	
	$t(10)$	P	ES	r	P
Area	3.08	0.011*	0.48	0.607	0.047*
RMSap	2.84	0.017*	0.44	0.696	0.017*
RMSml	3.47	0.005*	0.54	0.317	0.341
VMap	3.83	0.003*	0.59	0.421	0.196
VMml	3.87	0.003*	0.60	−0.295	0.377

Columns at the left show statistical results from *t* test comparisons (*t*, *P* and ES values) of COP measures obtained in the control and optimal stimulation (OS) conditions. Right columns show the results of the correlation tests (*r* and *P* values) between the reductions in COP measures and the reductions in force SD. *Asterisks* (*) indicate significant differences and significant correlations ($P < 0.05$)

significant differences between conditions ($F(3,7) = 5.804$, $P = 0.026$, ES $= 0.713$). Post hoc analyses showed significant reductions in plantar flexion force SD over the control condition when electrical noise was applied to TA and TS muscles simultaneously ($P = 0.011$) and to the TS muscle alone ($P = 0.029$). The reduction found between control condition and TA condition (an 11.3% reduction) did not reach statistical significance ($P = 0.091$). No significant differences were found for the remaining comparisons ($P > 0.3$); particularly, TA + TS did not present a significantly stronger effect than TS or TA alone, even though there was a tendency.

Discussion

Previous studies in the literature have shown that noise stimulation (electrical or mechanical) may improve balance control (Gravelle et al. 2002; Priplata et al. 2002, 2003, 2006; Ross 2007; Magalhaes and Kohn 2011; Kimura et al. 2011) under different paradigms (unipodal stance; foot sole, knee joint or finger stimulation). Deterministic electrical stimulation (bipolar balanced stimuli, pulse width 200 µs, frequency of 100 Hz) applied to the posterior aspects of the legs has also been shown to reduce postural sway

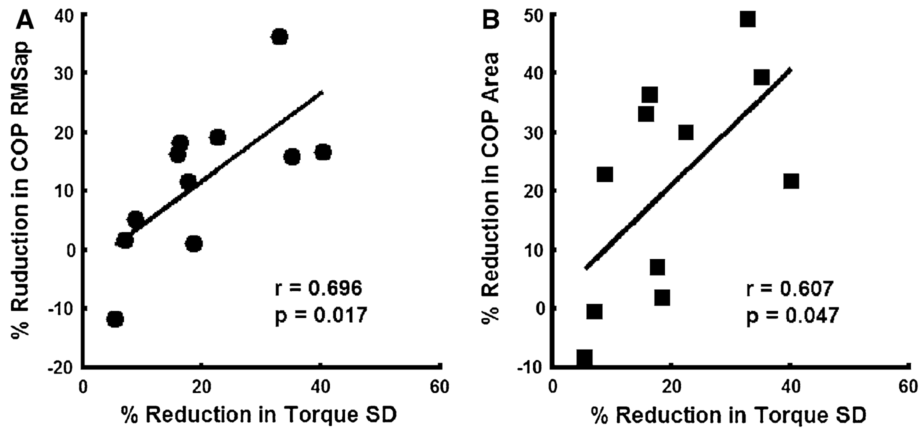

Fig. 4 Scatterplots of the percent reductions in torque SD as a function of the percent reductions in COP variables (**a** RMS; **b** Area) with electrical noise stimulation. *Superimposed lines* indicate the linear regression lines with statistical significance ($P < 0.05$)

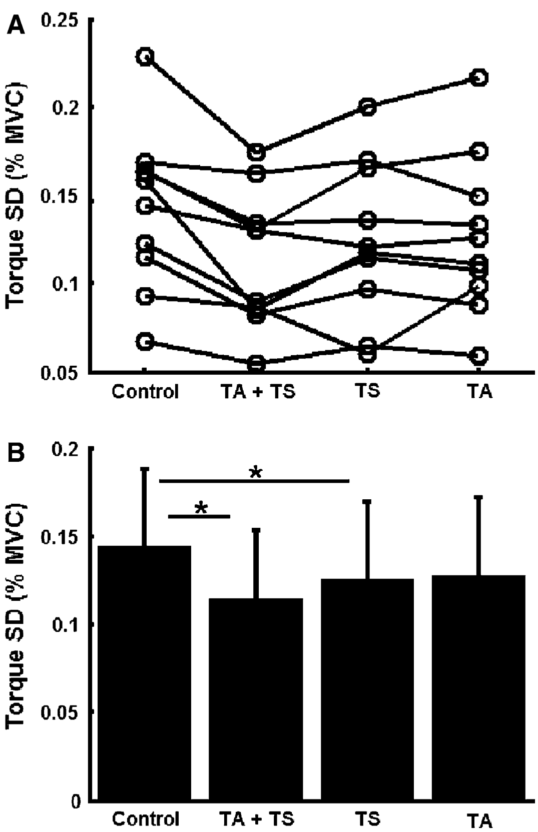

Fig. 5 Torque SDs computed from control and stimulation conditions (TA + TS, TS and TA) during Experiment 2. **a** Average torque SD values calculated for individual subjects. **b** Average group data ($n = 10$) calculated during control and stimulation conditions. TA + TS indicates the condition in which electrical stimulation was applied to the TA and TS muscles simultaneously, while TS (TA) indicates the condition in which electrical noise was applied separately to the TS (TA) muscle. *Asterisks* (*) indicate significant differences ($P < 0.05$) between conditions

(Dickstein et al. 2006). The present study extends these findings by showing that electrical noise applied bilaterally over the TS muscles reduces postural oscillations during bipedal quiet stance. The most striking result of the present investigation is that noise-based stimulation attenuates force variability during the maintenance of isometric plantar flexion forces. Moreover, we have found a significant correlation between the reduction in force fluctuation and the decrease in postural sway due to the electrical noise stimulation. This indicates that changes in plantar flexion torque variability obtained in response to a given subsensory random stimulation may provide an estimate of variations in postural sway amplitude under the same stimulation. As commented in the Introduction, one practical application of such a correlation is that the simple force-matching task may expedite the search for optimal stimulation parameters to reduce postural sway. In addition, the present study showed significant reductions in force variability when noise stimulation was applied to TS muscles alone and to the TA and TS muscles simultaneously. However, no significant reductions in force variability were found when noise was applied to the TA muscle alone, indicating that noise stimulation to the TA muscle may not be as effective as noise stimulation to the TS muscles, at least in improving force steadiness during an isometric force-matching task. These findings might have implications for understanding the proprioceptive role of the ankle muscles in controlling isometric steady contractions, as we shall discuss in more detail in the text ahead.

The electrical noise levels utilized in the present experiments were of low intensity, below sensory threshold. Therefore, the possibility that an attention/arousal mechanism had an effect in improving postural stability is discarded, since the subjects were "insensitive" to the stimulation conditions and no current was applied in the control condition.

Probable mechanisms

The present results are interpreted on the basis of a stochastic resonance mechanism, which is referred to an improvement in performance of a given system in response to an appropriate level of noise. The stochastic resonance phenomenon has been described in very different settings, ranging from applications in communication engineering to neural systems (McDonnell and Abbott 2009; McDonnell and Ward 2011). In the neurophysiology literature, a substantial number of publications have shown that there is an optimal range of noise intensity levels that enhances transmission of information across a given neural pathway (Collins et al. 1996; Manjarrez et al. 2002; 2003, 2007; Collins et al. 2003; Martinez et al. 2007; Magalhaes and Kohn 2011). In a simplified picture, the addition of levels of noise within an optimal range cause small receptor/membrane potential fluctuations that bring the neuron closer to threshold and hence make normally sub-threshold stimuli (e.g., small muscle length variations) detectable. In the context of optimizing neuromuscular control, studies have shown that postural sway can be attenuated by applying imperceptible noise stimulation (mechanical) to the soles of the feet (Priplata et al. 2002) as well as to the medial and lateral aspect of the knee (electrical) of standing subjects (Gravelle et al. 2002). For example, Gravelle et al. (2002) have suggested that the subsensory stimuli at the sides of the knee joint enhance the sensitiveness of joint proprioceptors causing a subsequent improvement in knee position sense that facilitates stance stability.

It is well known that muscle sensory organs, i.e., muscle spindles (sensitive to changes in muscle fiber length) and Golgi tendon organs (sensitive to changes in muscle tension), play a key role in the proprioception of movement (Rothwell 1994). Given the site of application of the electrical noise stimulation employed in the present experiments (which covered a large area over the muscles' bellies and included tendon regions) and the low level intensity of the stimulation (which favors the depolarization of large diameter afferents, for example types Ia and II afferents associated with muscle spindles and type Ib afferents associated with Golgi tendon organs), an improved sensitivity of these receptors (and hence a greater efficiency in the transmission of proprioceptive information) seems to be the probable mechanism behind the enhanced force and postural control observed in the present experiments.

Effects of TS stimulation on force variability and postural sway

For a passive muscle (i.e., with no active modulation), spindles are able to provide proprioceptive signals that are highly correlated with joint rotation (Matthews and Stein 1969; Matthews 1981). However, for an actively modulated muscle (e.g., the TS muscles during standing), variations in muscle activity cause the muscle fibers to shorten and lengthen and hence variations in muscle length represent a sum of an active (i.e., muscle activation) and a passive (i.e., joint rotation) components (Loram et al. 2009). As a consequence, the signal of interest (i.e., joint rotation) may be obscured at the source before transmission to the muscle spindles, and hence, variations in muscle length of the TS muscles may not reflect postural oscillations and ankle joint rotations (Lakie et al. 2003; Loram et al. 2004, 2005a, b, 2007, 2009). In this sense, it has been suggested that spindles in un-modulated muscles crossing the ankle joint, i.e., TA, might provide better proprioceptive information during standing than spindles in the actively modulated agonists, i.e., TS (Di Giulio et al. 2009).

The above-referred suggestion from the literature that active muscles may not provide useful proprioceptive information seems conflicting with the results from the present experiments, since electrical noise applied to the TS significantly improved the control of isometric muscle torque (Experiments 1 and 2) *and* postural oscillations (Experiment 1). However, the force-matching task relied on the maintenance of isometric contractions and hence proprioceptive influx from Golgi tendon organs and muscle spindles was determined by an active component (i.e., muscle activation) only. It is important to emphasize that even without the influence of ankle movements, information from muscles spindles may have contributed as a good source of proprioceptive feedback during the force-matching task, since muscle length variations were proportional to the force fluctuations (linear relationship from Hooke's law, $F = kx$, where F is the exerted force, k is constant representing tendon–muscle stiffness, and x is the muscle length). Therefore, enhanced sensitivity of muscle spindles (by noise stimulation) could have provided improved feedback about the exerted torque thereby improving force steadiness. One cannot rule out the possibility that the electrical stimulation also affected the proprioceptive structures of other muscles associated with the same joint (e.g., synergists of the TS), which are part of the population inflow of proprioceptive information reaching the central nervous system.

Effect of TA stimulation on force variability

In Experiment 2, we attempted to explore the effect of electrical noise stimulation applied over the TA muscle on the variability of plantar flexion torque fluctuations during the isometric force-matching task. Significant reductions in force variability with noise stimulation were observed when noise was applied to the TA and TS muscles simultaneously and when noise was applied separately to the TS muscles, while the reduction found when noise was applied to the TA muscle alone did not reach statistical significance. Since TA is passive during the isometric force-matching task and no considerable ankle movement occurs, TA may have been a poor source of muscle proprioceptive information, which might have accounted for the undetectable effect of TA stimulation over the control condition. Nevertheless, it is noteworthy that despite lacking statistical significance, noise stimulation to the TA caused an average reduction of 11.3% in force variability over the control condition. Furthermore, when noise was applied to the TA and TS simultaneously, there was a greater reduction in force variability compared to the condition in which noise was applied over the TS muscles separately (20.2% vs. 13.0% reductions over the control condition, respectively). Therefore, it seems that TA stimulation had some effect in reducing force variability, although such an effect could not be statistically confirmed with the present experiments, and hence, further investigations are needed in order to explore this issue.

Further considerations

In the present study (Experiment 1), the mean reduction in RMSap (strongly associated with plantar flexion torque fluctuations during stance) was 11.8%, much smaller than the mean reduction in force variability (21.1%) during the force-matching task. This would be expected since the neural feedback loops activated in the very stable force-matching task are part of a much more complex feedback control system that keeps the body from falling during quiet stance. These more complex feedback systems are associated with a higher number of degrees of freedom both from the mechanical and neural standpoints and, hence, less sensitive to the external electrical stimulation.

Another interesting observation from the present experiments is that there was a 21.1% reduction in torque variability with electrical noise applied to the TS muscles bilaterally (Experiment 1), while electrical noise to the right TS muscles (Experiment 2) resulted in a 13.0% reduction in torque variability. A direct comparison is not appropriate, since the experiments were conducted in different days, and hence, several factors (e.g., electrode repositioning, noise intensity effectiveness) could have accounted for this difference. Nevertheless, one may hypothesize that a crossed effect (Zhou 2000; Stubbs et al. 2011) may have played a role, through a mechanism in which electrical noise applied to the left leg may have contributed to improved force control exerted by the right leg.

Conclusions

The present results show that imperceptible electrical noise stimulation can be used to improve the control of a maintained isometric plantar flexion force with correlated improvements in postural control. Therefore, these results extend the current knowledge by showing that reductions in postural sway induced by a given level of electrical noise stimulation (applied to the ankle muscles) are associated with attenuations in isometric plantar flexion torque variability caused by the same stimulation. The present findings may have useful applications for the development of rehabilitation techniques to improve sensorimotor function in age- and disease-related deficits associated with impairments in the control of movement and balance. For example, a force-matching task with electrical noise stimulation may be used in the early stages of rehabilitation protocols designed to recover/maintain balance ability in different populations. Additionally, the choice of appropriate electrical noise stimulation parameters to enhance steadiness during quiet stance may be based on findings from noise-induced torque variability attenuation during force-matching tasks.

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