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ORIGINAL ARTICLE

Effects of aging and tactile stochastic resonance on postural performance and postural control in a sensory conflict task

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Abstract

Postural control in certain situations depends on functioning of tactile or proprioceptive receptors and their respective dynamic integration. Loss of sensory functioning can lead to increased risk of falls in challenging postural tasks, especially in older adults. Stochastic resonance, a concept describing better function of systems with addition of optimal levels of noise, has shown to be beneficial for balance performance in certain populations and simple postural tasks. In this study, we tested the effects of aging and a tactile stochastic resonance stimulus (TSRS) on balance of adults in a sensory conflict task. Nineteen older (71–84 years of age) and younger participants (22–29 years of age) stood on a force plate for repeated trials of 20 s duration, while foot sole stimulation was either turned on or off, and the visual surrounding was sway-referenced. Balance performance was evaluated by computing an Equilibrium Score (ES) and anterior–posterior sway path length (APPlength). For postural control evaluation, strategy scores and approximate entropy (ApEn) were computed. Repeated-measures ANOVA, Wilcoxon signed-rank tests, and Mann–Whitney *U*-tests were conducted for statistical analysis. Our results showed that balance performance differed between older and younger adults as indicated by ES ($p = 0.01$) and APPlength (0.01), and addition of vibration only improved performance in the older group significantly ($p = 0.012$). Strategy scores differed between both age groups, whereas vibration only affected the older group ($p = 0.025$). Our results indicate that aging affects specific postural outcomes and that TSRS is beneficial for older adults in a visual sensory conflict task, but more research is needed to investigate the effectiveness in individuals with more severe balance problems, for example, due to neuropathy.

Keywords

Aging, balance, foot sole vibration, stochastic resonance, tactile receptors

History

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Introduction

One major concern of the US health care system is improvement of the health of older adults and maintenance of their independence. Falls are the leading cause of traumatic death in older adults (Galica et al. 2009) and therefore the prevention of falls and fall-related injuries in older adults is an important area of research interest. Falls are a factor causing enormous costs for short and longer term patient care and putting a significant burden on the health care system. Each year, non-fatal and fatal falls lead to medical costs of approximately 19 billion and 200 million dollars, respectively (Stevens et al. 2006). Prevention of falls and related injuries is associated with increased quality of life by enabling older adults to remain more independent. Current research efforts are mainly focusing on either improving postural control by employing neuromotor training interventions or by utilizing assistive devices designed to improve complex and potentially impaired sensorimotor control in older adults.

It is believed that there are three major portions of postural control: (1) the sensation of position and displacement, (2) processing of afferent signals, and (3) selection and generation of adequate motor responses in order to ensure postural stability or to re-establish postural verticality (Schmidt 1975; Redfern et al. 2001). Due to extended research efforts since the 1990s, today there is a better understanding of modifiable and consistent risk factors associated with falls. For optimal postural control, complex sensorimotor mechanisms and processes are required. If any of the involved systems are perturbed, maintenance of postural control can become challenging.

It is well documented that aging negatively influences postural control processes leading to associated declines in balance performance and increases the risk of falls (Amiridis 2003; Shaffer and Harrison 2007; Seidler et al. 2010). More specifically, the vestibular, visual, proprioceptive, and cutaneous sensory sources become less sensitive to stimuli due to aging. Cutaneous receptors are important contributors of feedback about orientation of the body in space. The uniqueness of the plantar surface and mechanoreceptors of the sole of the foot is that it is a location on the body that directly connects humans to their environment. Plantar

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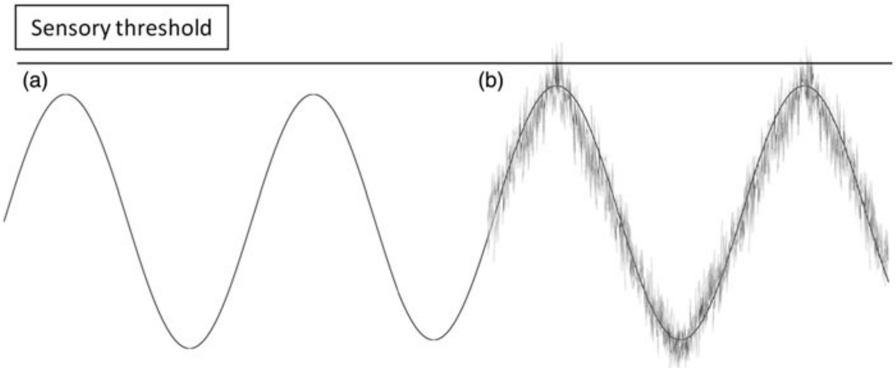

Figure 1. (Threshold) stochastic resonance. (a) Sinusoid signal does not reach threshold and is not detected. (b) Addition of optimum levels of noise makes the signal detectable and information content of the original signal is retained.

surface feedback has shown to be used to gather information about support surface characteristics in gait, but seems to be more important in postural control, by providing information about pressure changes and associated postural sway (Kavounoudias et al. 1998; Zhang and Li 2013). The importance of mechanoreceptors for postural control is further indicated by the fact that somatosensory decline in the feet has been recognized as a major predictor of falls in older adults (Magnusson et al. 1990; Patel et al. 2009).

Information provided by the mechanoreceptors assists in detecting the position of the center of mass over the base of support (Maki et al. 1999; Perry et al. 2000). Aging decreases the overall functioning of mechanoreceptors and affects stimulus detection (Verrillo et al. 2002). A higher detection threshold of the mechanoreceptors represents a lowered ability to efficiently and quickly respond to potential perturbations and balance disturbances. Many research efforts are aimed towards enhancement of aging sensory systems, delay of decline of the involved structures, or augmentation of sensory function.

One of the most common techniques to improve foot sole sensory function is modification of footwear, whereas several proprioceptive channels (muscle spindles and tactile receptors of the foot) can be affected via compression or specifically designed, textured shoes or sandals (Hijmans et al. 2007, 2009). This may lead to improved postural performance in younger (Corbin et al. 2007) and older adults (Hatton et al. 2011). A more complex intervention is the design of insoles that augment sensory processing by allowing direct modification of sensory detection mechanisms, such as the utilization of stochastic resonance (SR) effects in mechanoreceptors of the foot sole. SR describes an effect whose foundation is based on the concept of ‘‘positive noise’’ for improvements of the sensorimotor system during human movement or posture. Stochastic noise is ubiquitous in biological, specifically neural, systems (Faisal et al. 2008; McDonnell and Ward 2011). The most important feature is that an output signal becomes a better representation of the input signal when noise is added, in comparison to when there is no additional noise (McDonnell and Abbott 2009). One general assumption for utilization of noise-induction for biomedical purposes is that SR benefits sensory receptors' signal detection and processing in order to ultimately improve (motor) output. With an appropriate level of noise added to the sensory signal, signals can be detected more easily, since action potential thresholds are reached more rapidly, whereas without the noise addition, external signals remain at sub-threshold levels and therefore remain undetected (Figure 1). It is important to denote that the main difference between low-level stimuli and SR stimuli is that the latter are not perceivable (sub-threshold). Effects of SR on function have been investigated extensively in a variety of different somatosensory sources with the ultimate goal to improve motor/balance performance. One of the most remarkable approaches is the induction of electrical noise at the vestibular level (galvanic vestibular stimulation) to improve spatial orientation and perception of body verticality (Mulavara et al. 2011) or electrical stimulation at the knee or lower leg level in healthy adults and patients (Ross 2007; Collins et al. 2009, 2011; Ross et al. 2013). Mechanical, that is, tactile sensory afferent modification has been investigated as well, whereas SR stimuli applied to the fingertip could assist participants' balance in a sensorimotor task (Magalhães and Kohn 2011; Kimura et al. 2012; Mendez-Balbuena et al. 2012). A number of studies reported improved postural performance when applying low-level vibration noise at the feet and those benefits are more prominent in older adults or in stroke or diabetic neuropathy patients (Priplata et al. 2006), than in younger adults (Priplata et al. 2003).

In the current experiment, we chose to investigate the effectiveness of application of sub-threshold mechanical stimulation (i.e., noise) on the soles of the feet in an environment providing conflicting sensory information. This requires multimodal integration of information, and reweighting of sensory information from visual and somatosensory receptors. A sensory conflict describes the emergence of diverging sensory information from different sensory sources with the involved sensory systems seemingly providing conflicting information about a particular situation. Unreliable information has to be suppressed in the integration process, while reliable information needs to be upweighted by the central nervous system (CNS). One example is a set of specific external constraints, for example, standing on a stable support, while the visual environment is unstable. This is a representation of potentially balance-threatening situations that may occur in real life (e.g., when the visual surrounding is shifting due to moving objects in the environment). It is not yet clear whether tactile SR may be beneficial in such specific tasks, and whether the benefits differ between younger and older adults. To our knowledge, only one study investigated potential effects of sub-threshold vibration in younger adults' balance when a continuously rotating visual scene was presented (Keshner et al. 2014).

The current experiment was designed to explore differences between older and younger adults and to investigate if tactile SR modifies performance during a postural task that exposes participants to sensory conflicts. We hypothesized that (1) aging would affect performance and control in the sensorimotor task in this experiment, and (2) a tactile stochastic resonance stimulus (TSRS) intervention applied to the soles would induce changes in measured outcomes. Positive effects of TSRS would indicate that balance may be improved through the use of SR, not only in simple, but also in more complex and challenging postural tasks.

Methods and materials

This study was conducted according to University of Houston policies concerning the protection of participants in human research. The protocol was approved by the University of Houston Committee for the Protection of Human Subjects (CPHS). All participants in the study signed an informed consent form before participation.

Participants

Nineteen adults participated in the study. The younger group consisted of 10 participants (5 male and 5 female mean age 25.1 ± 2.3, weight 67.4 ± 12.4 kg, height 165.6 ± 9.6 cm). The older group consisted of 9 participants (2 male and 7 female, mean age 78.6 ± 5.4, weight 68.7 ± 16.0 kg, height 165.1 ± 10.6 cm).

Inclusion and exclusion criteria

To be included in the study, prospective participants had to be free of any significant medical conditions, which included both physical and cognitive impairments. Age range for inclusion in the study was 20–35 years of age for the younger age group and 70–85 years of age for the older age group. The age range for the older adults group was based on existing knowledge about the onset of sensory decline and associated higher risk of falls. Physical health and inclusion in the study were determined based on a modified version of the Physical Activity Readiness Questionnaire (PAR-Q). Due to the nature of the experiments, only individuals without cognitive impairments, as represented by a score of 27 or higher on the Mini-Mental State Examination (MMSE; Folstein et al. 1975) were included in the study. Due to the potential effects of obesity on postural stability, detection of tactile stimuli and suppression of the generated vibration from the foot sole stimulators, individuals with a body mass index (BMI) $>30\,\text{kg/m}^2$ (BMI = mass (kg)/(height $(\text{m})^2$)) were also excluded. Sensory thresholds are elevated in most older adults, due to physiological and anatomical changes based on the effects of aging (Kenshalo 1986; Perry 2006). To determine whether potential participants should be included in the study, it was evaluated whether they actually displayed such a decrease of tactile sensitivity. The sensory thresholds of all potential participants were tested using a Semmes–Weinstein Monofilament (5.07/10g).

Task and apparatus

TSRS of each foot sole was administered by embedding three vibration tactors (C-2; Engineering Acoustics, FL, USA) within a custom-made ReoFlex® 50 urethane rubber sole (Smooth-on, Easton, PA, USA) with a hardness of Shore 50A. The location for the tactors was set to position them under the first metatarsal, the fifth metatarsal, and the heel. The rubber soles were adjustable so they could be personalized to the participant's foot size. All six tactors were connected to a control box which included a white-noise generator. For the current experiment, a white-noise signal was added to a generated sinusoidal signal band-limited to 1 Hz to about 500 Hz, thereby including vibration frequencies that encompass the response bandwidth of mechanoreceptors of the foot sole. Customized software was created to allow the investigators to manipulate stimulus magnitude as required using a guided user interface displaying magnitude of stimulus as percentage of maximum vibration output.

Protocol

For the initial Semmes–Weinstein test, participants were sitting barefoot in a chair. The test was administered according to instructions provided with the Monofilaments and was based on a forced-choice method. The test locations were the first metatarsal of both feet. Four trials were performed on each foot. Older adults were included if they exhibited sensory impairments as indicated by an inability to feel the stimulus on either of the two feet in more than one trial on each foot. All younger and older participants of the study were familiarized with the experimental soles containing the tactors and were also familiarized with the task. For determination of vibration threshold and optimal experimental stimulus magnitude/amplitude (approximately 90% of sensory threshold intensity), a vibration test was conducted with each younger and older participant. This was done because a stimulus intensity level of 90% has been shown to be effective in eliciting the positive postural performance effects of sub-threshold vibration (Priplata et al. 2002, 2006; Hijmans et al. 2008). The threshold was determined by a method of levels (Shy et al. 2003) binary search.

In the main experiment, all younger and older participants stood on the vibrating soles, placed on top of the force plate of the NeuroCom (Balance Master®; NeuroCom Intl, Clackamas, OR, USA). Foot position was determined by the NeuroCom system and was based on the participant's height. A safety harness was attached to secure participants in case of a fall and they wore headphones (providing white-noise sound) during experimental trials to cancel noise generated by the NeuroCom. Participants stood on the force plate for six consecutive 20 s trials, with 30 s breaks between each trial. Tactile SR was randomized across participants into blocks of three trials. That is, three consecutive trials either with or without TSRS. Participants were blinded regarding the condition of each trial, so they were not aware whether TSRS was turned on or off during each specific trial. The surrounding visual environment of the NeuroCom was sway-referenced, so it rotated proportionally to the postural sway of the participant. Therefore, vision was no longer a reliable determinant of postural orientation since the visual surround moved in phase with the individual. The support surface (force plate) was stationary and stable during all trials. Prior to the start of each trial, participants were instructed to look straight ahead, and to stand as quiet as possible throughout the whole trial, while folding their arms in front of their chest. After a block of three trials, there was a 2-min rest period, during which participants sat in a chair.

Data reduction

Center-of-pressure (COP) data were computed based on force data acquired using a force plate system (NeuroCom EquiTest, NeuroCom Intl). Force plate data were collected at 100 Hz and processed via Windows-based software on a connected computer (Research module, NeuroCom software version 8.0, NeuroCom Intl).

Outcome measures were calculated from measurements recorded via the force plate during experimental trials. A custom MatLab (MatLab 7, Mathworks, Natick, MA, USA) analysis script was used to generate outcome measures for analysis. All outcomes were based on either postural *performance* or postural *control*. For performance, we computed an Equilibrium Score (ES) calculated from force plate data of each trial (20 s @ 100 Hz, 2000 data points). The outcome was derived from maximum anterior–posterior center-of-gravity (COG) displacements and a theoretical maximum excursion (12.5 degrees), and calculated using the following formula:

$$\mathrm{ES} = \frac{12.5 - [\theta_{\max} - \theta_{\min}]}{12.5} \times 100.$$

The result is usually provided as an inverse percentage of 0–100. No movement results in an ES of 100, whereas a fall results in a score of 0. As a second balance performance measure, anterior–posterior sway path length (APPlength) was calculated by summarizing the total displacement of COP (as calculated from force plate data) for each 20-s trial.

For postural *control* evaluation, approximate entropy (ApEn), a non-linear analysis tool based on regularity/predictability of a time series was applied. ApEn values were calculated for each trial. The calculation and associated surrogate analysis were conducted based on methods described previously (Pincus 1991; Theiler et al. 1992), whereas the methods have been applied in a variety of studies (Cavanaugh et al. 2006; Ocak 2009; Dettmer et al. 2013). Computation of ApEn generates a single value per time series that describes the predictability of the sequence.

The second postural control measure was a strategy score, based on analysis of shear forces exerted on the force plate. For computation, peak-to-peak amplitude of the shear oscillation was compared to the maximum possible shear of 25 pounds, and expressed as a percentage value, a score of about 100 indicates a strategy based solely on ankle rotations and 0 represents a strategy solely based on hip movements (Speers et al. 1999). The formula for calculation is based on minimum and maximum shear forces (SH):

$$\frac{\mathrm{SH}_{\max} - \mathrm{SH}_{\min}}{25} \times 100.$$

Statistical analysis

Several sets of data were not normally distributed, which required the utilization of non-parametric statistical testing. In an initial step, we evaluated potential adaptation effects due to repetition of the task. There was significant adaptation; however, there was no condition-by-time effect. Results were averaged over all three trials performed in each condition for further analysis.

Main outcomes were ES and APPlength for evaluation of postural *performance*, and ApEn and strategy score for investigation of postural *control*. Mixed-model ANOVA, 2×2 repeated-measures analysis with one between factor (age) and one within factor (vibration condition) was conducted via SPSS (IBM Corp., Somers, NY, USA). There were 10 younger and 9 older adults included in the statistical analysis. In the case of non-normality of experimental data (APPlength and ES in the younger group), we applied alternative, non-parametric statistical analysis. In that case, a Wilcoxon signed-rank test was utilized to analyze relationships between pairs of related samples; the Mann–Whitney *U*-test was used for analysis of pairs of independent samples. Significance of statistical comparisons was tested at the $p < 0.05$ level, whereas Bonferroni correction of alpha levels was applied to account for multiple comparisons. Effect sizes were calculated for each significant comparison according to established methods for parametric and non-parametric tests (Fritz et al. 2012).

Results

Assessment of foot sensory detection thresholds revealed that the 90% level of threshold in the younger group (2.1% ± 0.56) was significantly less than in the older participants (23.2% ± 21.8), $t(9.012)$, $p = 0.013$. One participant in the older age group experienced a short episode of postural instability which led to subsequent lowered performance over the remaining trial (beyond 3 standard deviations of the mean change between experimental conditions). Since this drop cannot be attributed to the effects of TSRS, the force data of this participant was removed. The remaining data were then analyzed for potential differences between groups and conditions as indicated in the Methods section. Mean postural *performance* data are presented in Table I.

It was observed that APPlength differed significantly between older and younger adults without TSRS, $U = 9.0$, $p = 0.02$, $\eta^2 = 0.45$ but not with the SR stimulus added (Figure 2). APPlength was significantly reduced by TSRS only in the older group, $F(1, 8) = 11.119$, $p = 0.01$, $\eta^2 = 0.58$.

The same response pattern was observed for ES, where ES was significantly higher in the younger group than in the older group without TSRS, $U = 14.0$, $p = 0.010$, $\eta^2 = 0.34$, but not with TSRS added. Further analysis of TSRS effects in the older group revealed that there was a significant improvement in ES in the older adults group with the addition of TSRS, $F(1, 8) = 10.606$, $p = 0.012$, $\eta^2 = 0.57$ (Figure 3).

In addition to performance, postural *control* characteristics were analyzed using ApEn and strategy scores. The group means data are reported in Table II. Analysis of strategy scores (Figure 4) revealed a significant group effect, $F(1, 17) = 8.313$, $p = 0.01$, $\eta^2 = 0.32$ and a group by TSRS condition interaction, $F(1, 17) = 4.481$, $p = 0.049$, $\eta^2 = 0.20$. Further analysis showed a significant effect of TSRS on strategy scores in the older group, $F(1, 8) = 7.540$,

Table I. Postural performance of older adults (OA) and younger adults (YA) in sensory conflict experiment.

	ES		APPlength (in cm)	
	YA	OA	YA	OA
No vibration	92.3 ± 3.7	88.18 ± 4.1	12.1 ± 3.7	25.6 ± 10
Vibration	91.9 ± 3.1	90.6 ± 2.8	12.3 ± 3.2	19.6 ± 9.1

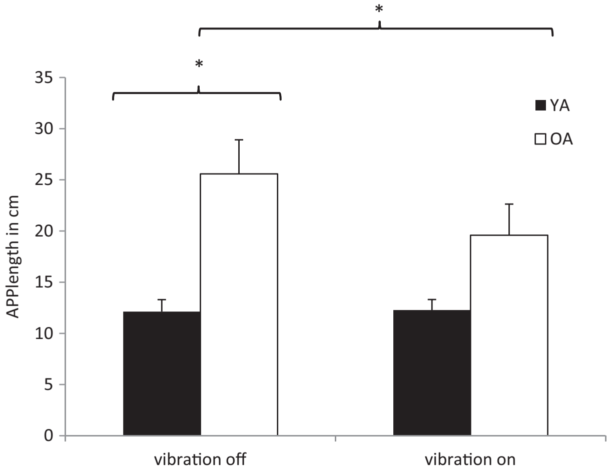

Figure 2. APPlength means (over three trials) and standard error, younger adults (YA) and older adults (OA). * = $p < 0.05$.

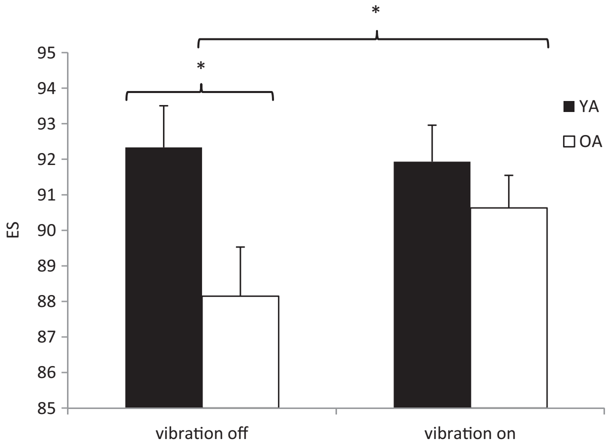

Figure 3. ES means (over three trials) and standard error, younger adults (YA) and older adults (OA). * = $p < 0.05$.

Table II. Postural control measures of older adults (OA) and younger adults (YA) in sensory conflict experiment.

	Strategy score		ApEn	
	YA	OA	YA	OA
No vibration	98.5 ± 0.4	97.1 ± 0.9	0.59 ± 0.17	0.67 ± 0.18
Vibration	98.3 ± 0.6	97.7 ± 1.1	0.57 ± 0.11	0.67 ± 0.16

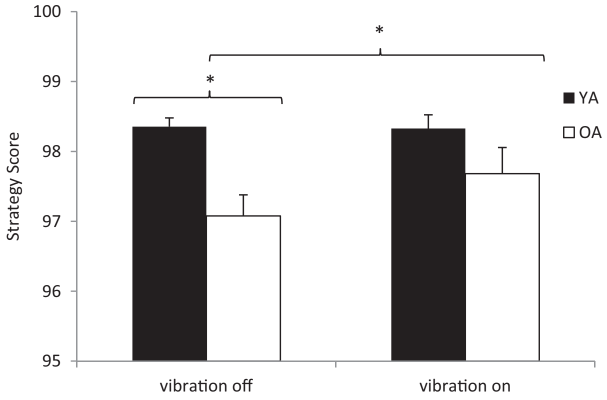

Figure 4. Strategy score means (over three trials) and standard error, younger adults (YA) and older adults (OA). * = $p < 0.05$.

$p = 0.025$, $\eta^2 = 0.46$. There were no significant group or TSRS effects on ApEn.

Discussion

This study was designed to investigate the association of aging with a complex postural task that included a sensory conflict, and the potentially differential effects of introducing mechanically generated sub-threshold noise to the soles of the feet on a number of different postural measures.

Effects of aging

We hypothesized that age would be associated with both performance and control characteristics in this experiment. Older adults exhibited slightly decreased postural performance compared to younger adults, as evidenced by lower ES and greater APPlength. This confirms earlier results related to a postural performance decline with aging (Cohen et al. 1996; Forth et al. 2007). In our experiment, participants were required to resolve a sensory conflict, in that available visual information was not useful for determining the body's orientation. This resulted from the fact that the visual surround moved in a manner proportional to the pressure applied to the support surface so that the participants did not experience a visual flow field and therefore could not visually detect self-motion. This specific task may be challenging to older adults due to a number of sensory- and motor-related aging processes (Bugnariu et al. 2007). Maurer et al. (2001) proposed the idea of two different main aspects of foot sole cutaneous signals, the evaluation of the body's orientation in space and investigation of support characteristics. Aging affects the function of foot sole feedback, and earlier results suggest that sensory decline affects threshold characteristics when facing complex multimodal stimuli. This in turn could lead to an increased shift of reliance towards vision. During optimal visual conditions, this might be a valuable strategy to compensate for somatosensory decline, but it affects postural performance and even poses a risk when visual information is not reliable (Bugnariu et al. 2007).

Results from the strategy score analysis showed that older adults in general exhibited a slightly lower strategy score. This is expected when visual information is unreliable and has been shown to be a typical response in older adults (Liaw et al. 2009). The aging-related change may represent part of a set of compensatory mechanisms, like co-contraction of the lower leg musculature, which leads to stiffening of the lower limb, and associated decreased reliance on proprioceptive feedback (Benjuya et al. 2004). Additionally, a strategy involving more hip movement allows individuals to exert higher shear forces to the support surface, allowing for quicker movement or correction of the center of mass. However, the differences between groups, although being statistically significant, were minimal (about 1.4 points in the strategy score). It is debatable whether this small difference has physiological or functional relevance. The reason for the small group differences presumably can be attributed to the overall high level functioning in the older adults group.

Postural control characteristics, as measured by the nonlinear measure of ApEn, did not significantly differ between age groups, indicating that regularity of COP sway did not differ between older and younger adults. The finding that age was not associated with ApEn in the context of the current postural task was unexpected, since results from earlier postural studies suggested that changes in predictability of a time series (ApEn) reflect aging processes, and suggesting a decrease in availability of sensory information or adaptability of the system (Manor et al. 2010). In comparison, earlier evidence showed decreased regularity in older adults in specific postural tasks (Borg and Laxåback 2010). Usually, the observed differences in ApEn can be interpreted as: (1) an aging-related mechanism that decreases or increases sway complexity; and/or (2) indicative of a different motor control strategy. In the latter case, more muscle co-contraction in the lower legs and associated stiffness around the ankles would lead to a less complex motor output. The older group in this study, despite exhibiting elevated sensory thresholds, was able to perform at levels that were not different from the younger group. The limited decline of sensorimotor abilities in our older group potentially was too small to be expressed in significantly different ApEn values. The pressure distribution and changes thereof sensed due to sway activity seemed to be sufficient in this group to provide the CNS with enough information to interpret and integrate sensory information for postural control in a manner similar to the younger participants. Alternatively, it is possible that statistical power was insufficient to detect differences, due to the small sample size included in the statistical analysis.

Effects of TSRS

The current study provides new knowledge regarding effects of SR in a specific sensory conflict task that resembles real-life situations in which individuals are exposed to unreliable visual information. We hypothesized that the addition of TSRS would affect performance and control in the current postural task. Our results showed a lack of TSRS effects on sway parameters in the younger group which is in concordance with most existing literature. Priplata et al. (2002) reported an effect on sway parameters when adding noise to the foot sole, however, this effect was larger in older than in younger adults. Additional results suggest that postural control (due to sensory feedback) is already near optimal in younger adults (Wu et al. 2007), thus a TSRS intervention might not result in foot sensory information enhancement such that performance is positively impacted. Based on results from earlier experiments, including diabetes and stroke patients (Priplata et al. 2006), it can be argued that the benefits from SR vibration applied to the feet are related to initial baseline performance: those individuals who exhibit larger postural sway and instability during baseline trials benefit more from the intervention than those with near-optimal control (e.g., healthy adults between the ages of 18 and 35).

Our findings support the idea of benefits of a TSRS intervention predominantly in older participant populations with lower balance performance. Balance performance was slightly improved by the intervention, as ES increased in the older adults (by about 2.5 points). Although this difference appears small (considering the ES continuum of 0–100), it has to be noted that the baseline performance in the older group was already high. With the addition of TSRS, older adults approached the performance level of younger adults. This demonstrates that postural performance can be improved when augmentation of sensory feedback is induced in a group of older adults.

The effects of the TSRS intervention observed in the current study are not as pronounced as in earlier studies (Gravelle et al. 2002; Priplata et al. 2002). Our results are more similar to the smaller effects that Hijmans et al. (2008) reported in a study with neuropathic and healthy adults performing postural tasks (eyes open vs. eyes closed and added concurrent cognitive task). These authors found an effect of TSRS mainly in the patient group, and in more challenging task conditions, but not in the age-matched healthy group. Hijmans et al. concluded that the larger effects reported in earlier studies might to some extent stem from a different approach to balance evaluation. They reported that in some earlier experiments a single shoulder marker for determination of postural sway was applied. This may have contributed to the results compared to methodological approaches based on force plate data. A marker attached to the shoulder section would only be reliable in conditions where a perfect inverted pendulum model of human postural control is assumed, without any hip or upper body contribution.

One of the performance measures in this experiment was ES, which is based on peak-to-peak sway angles. Sway has traditionally been interpreted as an indicator of postural stability, however, it is also possible to view sway as an indicator of a functional strategy that augments information detection and flow in postural control (Bringoux et al. 2003; Thedon et al. 2011). In view of this perspective, postural performance data from our experiment could be interpreted as an indicator of improved sensory flow from foot sole mechanoreceptors, requiring less ''exploratory'' sway to determine body orientation. This idea is supported by APPlength data from the older age group that showed a decrease of the sway path length with addition of TSRS. It is possible that sway is not solely an indicator of postural instability, but potentially represents an effort to increase feedback from the foot plantar surface and lower legs. The decrease of anterior–posterior sway path length in older adults could indicate that less sway was required to enhance feedback, since the intervention had affected/enhanced sensory system functioning. This would represent a decrease of required exploratory behavior to gather sensory cues for determination of postural orientation and subsequent control.

Alternatively, the sensory augmentation from the foot soles might affect the process of sensory reweighting that is required in the specific task. It is mandatory for effective postural control during the visual sway-reference task that visual information is suppressed in the CNS and an upweighting of somatosensory information occurs. There are inter-individual differences regarding this process, which could be related to functioning levels of the specific sensory systems and selection processes. Peterka and Black (1990) showed that even in the case of unreliable (sway-referenced) visual cues, some individuals still suppress vestibular or somatosensory cues while relying on (false) visual information, leading to higher instability.

The reasons for this persistence on visual dependency in the face of incomplete or inaccurate visual information are not yet known, but it would be valuable to investigate whether improved somatosensory feedback could affect this phenomenon in visually dependent individuals.

Postural control as expressed by the strategy score was significantly affected by TSRS in the older group. Addition of TSRS leads to a slight increase of strategy scores. Although the effect was very small, this could indicate that there was increased emphasis on using sensory feedback and a bottom-up strategy incorporating the (augmented) sensory feedback from the feet. Closed-loop-based postural control, including the constant analysis of sensory feedback, could become more efficient with the effects of SR added via sub-threshold vibration in an experimental older group of participants.

ApEn was not affected by TSRS in the current experiment. It is likely that the changes observed in other measures when adding a tactile stimulus are due to the different aspects of postural features detected by each measure. ApEn, which is based on regularity of the time series, differs from strategy scores, which are computed based on shear forces exerted to the force plate through the feet. Temporal dynamics of COP variability in the current experiment are either not affected by TSRS per se, or the effects are too small to be detectable.

Results from the current experiment provide evidence that aging is associated with specific changes in measures of postural control and motor performance, whereas not all measures are representative of this association. The different measures of postural performance in this experiment show how specific outcome measures may be able to detect different features of postural stability and performance. ES are based and therefore limited to peak-to-peak sway angles in each trial, whereas APPlength is not necessarily affected by several large COP excursions but by COP displacements throughout a whole trial. Therefore, the different analysis tools investigate different features of postural performance, which may explain some discrepancies between results for each outcome measure.

An intervention based on foot sole vibration could have value for improving balance in sensory conflict tasks, whereas improved sensory transmission and detection could lead to a better integration of somatosensory cues in situations where increased reliability of those cues is required. It is expected that older adults rely more on visual information than younger adults in some tasks, mainly due to decline of lower leg feedback structures and functioning. It is possible that the observed improvement of postural performance is a reflection of improved sensory feedback. Lower leg and plantar surface feedback is then favored over visual feedback in integration processes of the CNS and used to a greater extent in postural control in the sway-referenced environment provided in our experiment. More research is needed to determine the efficacy of the intervention in individuals who are prone to falls or exhibit significant loss of postural performance.

Declaration of interest

The authors report no conflicts of interest.

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