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Research paper

Subliminal electrical and mechanical stimulation does not improve foot sensitivity in healthy elderly subjects

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ABSTRACT

Objective: Deterioration of cutaneous perception may be one reason for the increased rate of falling in the elderly. The stochastic resonance phenomenon may compensate this loss of information by improving the capability to detect and transfer weak signals. In the present study, we hypothesize that subliminal electrical and mechanical noise applied to the sole of the foot of healthy elderly subjects improves vibration perception thresholds (VPT).

Methods: VPTs of 99 healthy elderly subjects were measured at 30 Hz at the heel and first metatarsal head (MET I). Participants were randomly assigned to one of five groups: vibration (Vi-G), current (Cu-G), control (Co-G), placebo-vibration (Pl-Vi), and placebo-current (Pl-Cu). Vi-G and Cu-G were stimulated using 90% (subliminal) of their individual perception thresholds for five minutes in a standing position. Co-G received no stimulation. The placebo groups were treated with mock stimulation. VPTs were measured twice before the intervention (baseline (BASE) and pre-measurement (PRE)), and once after the intervention (post-measurement (POST)).

Results: Significant differences were found between measurement conditions comparing BASE and POST, and PRE and POST. VPTs between groups within each measurement condition showed no significant differences. Vi-G was the only group that showed significantly higher VPTs in POST compared to BASE and PRE, which contradicts previous studies.

Conclusion: We analyzed increased VPTs after subliminal mechanical stimulation. The pressure load of standing for five minutes combined with subliminal stimulation may have shifted the initial level of mechanoreceptor sensitivity, which may lead to a deterioration of the VPT. The subliminal electrical stimulation had no effect on VPT.

Significance: Based on our results, we cannot confirm positive effects of subliminal electrical or mechanical stimulation on the sole of the foot.

1. Introduction

1.1. Sensitivity and aging

Aging is a complex process that is accompanied by numerous degenerative processes. Besides changes in musculoskeletal, proprioceptive, visual, and vestibular systems, the elderly have a reduced perception of cutaneous stimuli, which promotes falling in this population (Collins et al., 2003; Dhruv et al., 2002; Gillespie et al., 2012; Shaffer and Harrison, 2007). In several studies, Kavounoudias et al. (1998, 1999, 2001) demonstrated that vibration-induced sensory messages from mechanoreceptors in the sole of the foot are related to the regulation of upright body posture. Furthermore, Hämäläinen et al. (1992) found a positive correlation between quasi-static balance tasks and vibration sensitivity at 20 Hz in patients with unilateral sensory impairment. A recent study simulated the effects of reduced plantar sensitivity by cooling the sole of the foot (Germano et al., 2018). Reduced somatosensory input led to decreased balance control in healthy young subjects (Germano et al., 2018).

1.2. Stochastic resonance

Exercise intervention, such as strength, coordination, balance, or sensorimotor training, is reported to be an effective method to prevent unexpected falls (Gillespie et al., 2012). Furthermore, it

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is speculated that in addition to exercise intervention, different stimulating procedures may improve the sensitivity of plantar receptors to support fall prevention. The phenomenon behind this theory is called stochastic resonance: Noise can improve the capability to detect weak stimuli or enhance the information content of a signal (Haas et al., 2006; Hänggi, 2002; Iliopoulos et al., 2014; Moss et al., 2004). The stochastic resonance phenomenon requires the presence of (a) a subliminal stimulus, (b) a threshold, and (c) noise (Hänggi, 2002; Moss et al., 2004). There are two possible mechanisms behind this phenomenon. First, the noise adds energy to the subliminal stimulus and thus increases the transmission through the skin (Khaodhiar et al., 2003; Liu et al., 2002; Priplata et al., 2002; Richardson et al., 1998; Wells et al., 2005). Second, noise directly influences receptors by causing small changes in transmembrane potentials, which results in a higher level that is closer to the depolarization threshold (Dhruv et al., 2002; Gravelle et al., 2002; Khaodhiar et al., 2003; Kimura and Kouzaki, 2013; Magalhães and Kohn, 2012, 2014).

1.3. Mechanical stimulation

Several studies analyzing effects on postural control reported improvements while applying subliminal noisy mechanical stimulation to the sole of the foot of younger and elderly adults (Priplata et al., 2002, 2003). Moreover, stimulation with subliminal mechanical noise may improve the perception of subliminal tactile stimuli at the hand (Collins et al., 1996, 1997; Liu et al., 2002) or the sole of the foot (Cloutier et al., 2009; Khaodhiar et al., 2003; Liu et al., 2002; Wells et al., 2005). Cloutier et al. (2009) and Khaodhiar et al. (2003) examined vibration perception thresholds at the sole of the foot using a biothesiometer. Due to the poor repeatability of vibration perception thresholds, its application as a research tool is controversial (Schlee et al., 2012). Liu et al. (2002) and Wells et al. (2005) tested the effect of mechanical stimulation on vibration perception thresholds using a more reliable digitally controlled program at different frequencies. They attributed the improvements in vibration perception thresholds to a masking effect – an optimal noise level added an optimal amount of energy to a subliminal vibration signal to make it noticeable without information loss (Liu et al., 2002; Wells et al., 2005).

1.4. Electrical stimulation

The application of subliminal electrical noise to the knee joint (Gravelle et al., 2002), or to different muscles of the lower extremity (Magalhães and Kohn, 2012, 2014) also showed improvements in balance control. Moreover, the combination of subliminal electrical noise stimulation at the shank and coordination training resulted in higher improvements in postural stability than coordination training by itself (Ross and Guskiewicz, 2006; Ross et al., 2007). There are only a few studies that have investigated the effects of subliminal electrical noise stimulation on sensory perception at the hand (Iliopoulos et al., 2014; Richardson et al., 1998) or the foot (Dhruv et al., 2002). Dhruv et al. (2002) studied the effects of electrical noise stimulation on tactile stimuli at the sole of the foot. They placed adhesive electrodes medially and laterally at the first metatarsal head and tested tactile perception using Semmes-Weinstein monofilaments. During subliminal electrical stimulation, seven of the nine subjects showed an improved *pressure* perception (Dhruv et al., 2002). However, we did not find any studies which examined the effects of subliminal electrical stimulation on *vibration* perception thresholds.

1.5. Objectives

In summary, in most of the referenced studies, the number of study participants is small, the described effects are weak, and the methodological information to the signal characteristics is insufficient. Furthermore, to our knowledge, there are no studies which examine the effects of electrical stimulation on vibration perception thresholds. Therefore, our study addressed the following research questions: (1) Does subliminal electrical stimulation improve vibration perception thresholds on the sole of the foot? (2) Is mechanical or electrical stimulation more effective? Referring to the studies with subliminal stimulation, we hypothesized that subliminal mechanical and electrical stimulation - applied to the sole of the foot of healthy elderly subjects - improves vibration perception thresholds. Insofar as subliminal noisy stimulation shows improvements in vibration perception, technical everyday applications in the form of socks with integrated electrodes or vibrating insoles may be realistic solutions in fall prevention.

2. Materials and Methods

2.1. Participants

Ninety-nine healthy elderly (>60 yrs, 60 ♀/39 ♂, mean ± SD: 68.8 ± 6.0 yrs, 165.9 ± 19.3 cm, 75.1 ± 13.0 kg) participated in this study. Before the subjects gave their written consent, they were informed about the aims of the study and checked for exclusion criteria by medical screening. All participants were free of any diseases that could affect the sensory system (diabetes mellitus, peripheral neuropathy, neurological diseases, etc.). In case of any discomfort, participants were instructed to stop the measurements immediately. All procedures were performed in accordance with the recommendations of the Declaration of Helsinki and approved by the local ethics committee (V-068-17-HS-KK-Gesunde_07112014).

2.2. Preparation

Participants were randomly assigned to one of the following groups: mechanical vibration (Vi-G), current (Cu-G), control (Co-G), placebo-vibration (Pl-Vi), and placebo-current (Pl-Cu) (Fig. 1).

Before starting data collection, subjects were given a ten-minute acclimatization period to become accustomed to the room temperature. All subjects performed the following procedure for each anatomical location (first metatarsal head (MET I) and heel): baseline measurement (BASE), pre-measurement (PRE) as a reliability test, and post-measurement (POST) after treatment period. The mean out of three vibration perception threshold (VPT) measurements was used for statistical analysis. Between pre- and post-measurements, subjects were stimulated for five minutes in a standing position using 90% of their individual perception threshold of the mechanical (Vi-G) or electrical (Cu-G) signal. The control group did not receive any stimulation while standing for five minutes. Similar to Vi-G or Cu-G, the placebo groups were treated using the same procedure but with a mock stimulation (Fig. 1).

2.3. Procedure

VPTs were measured at two anatomical locations (MET I (Fig. 2a) and heel (Fig. 2b)) of the right foot using a modified vibration exciter (TIRA GmbH, model TV51075, Schalkau, Germany). The test person sat on a chair with their feet on the footrest and 90° knee flexion, and the right foot was placed onto the probe. Vibration frequency was chosen to be 30 Hz, a frequency which primarily innervates FA I cutaneous afferents (Johansson et al., 1982; Toma and Nakajima, 1995). This frequency is commonly used to test the vibration perception of Meissner Corpuscles in plantar sensory measurements (Nurse and Nigg, 1999; Peters et al., 2016). The vibrating metal probe (7.8 mm in diameter) protruded 2 mm through a 10 mm hole in a self-constructed wooden footrest

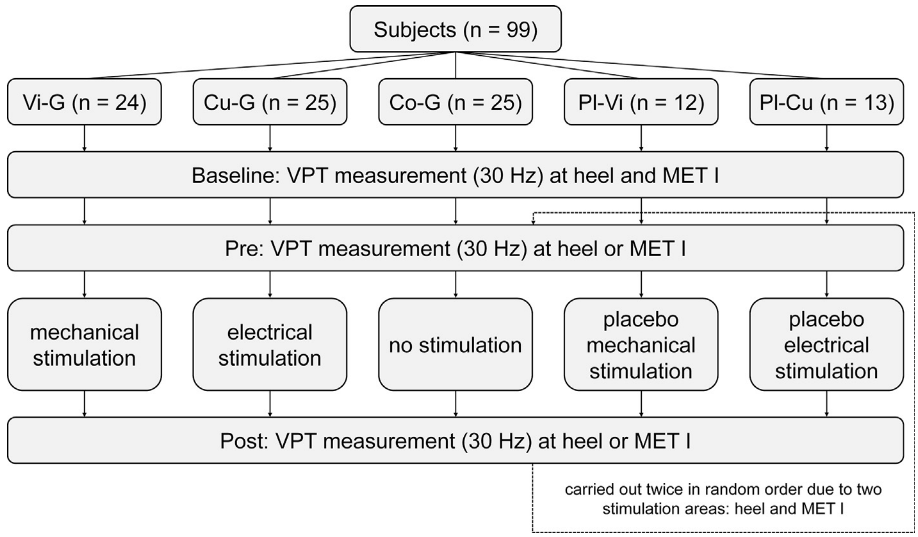

Fig. 1. Study design with vibration group (Vi-G), current group (Cu-G), control group (Co-G), placebo-vibration group (Pl-Vi), and placebo-current group (Pl-Cu). MET I: first metatarsal head. VPT: vibration perception threshold.

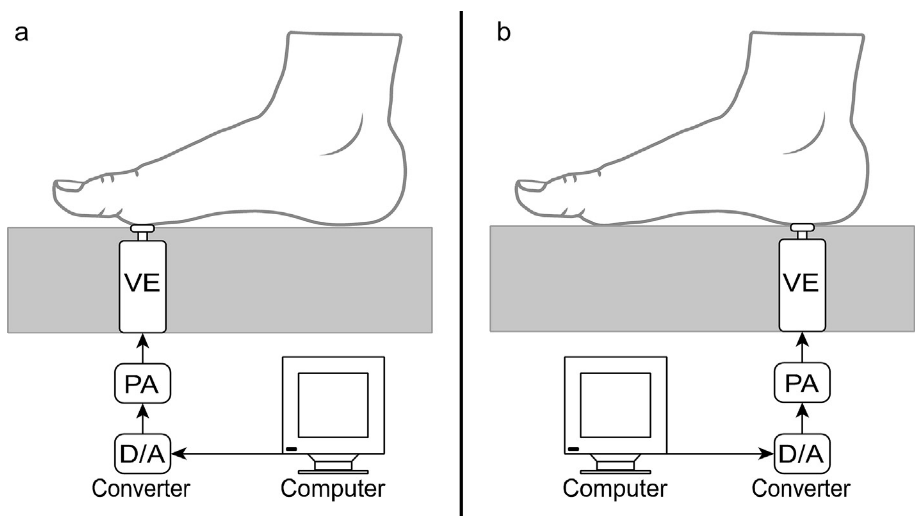

Fig. 2. Vibration perception threshold measurement at the first metatarsal head (a) and heel (b). The corresponding anatomical region could be precisely placed over the probe of the vibration exciter (VE). PA: power amplifier; D/A Converter: digital to analogue converter.

(650 mm * 600 mm * 300 mm) with a plastic plate on top. Vibration could be precisely applied to the required anatomical area by placing it directly onto the probe (Fig. 2).

Subjects wore noise cancelling headphones (QuietComfort 25 Acoustic Noise Cancelling headphones, Bose Corp., Framingham, USA) to avoid any environmental noises. Since sensitivity is related to plantar temperature (Schlee et al., 2009), foot temperature was measured and controlled using an infrared-thermometer (Mini Flash, TFA, Germany). Furthermore, room temperature was measured and controlled at 23 ± 2 °C (EN ISO/IEC 17025) using a thermometer (C28 Hand Held Digital Type K, Comark, UK).

2.4. Intervention

2.4.1. Current-group (Cu-G)

A two-channel stimulation current unit (Physiomed Elektromedizin AG, Germany) generated a stochastic biphasic current, which consisted of short triangular pulses with a duration of 1 ms. The pause times between the pulses were between 10 and 100 ms and were regulated by a micro-electric random generator. This resulted in a random stimulus pattern with a frequency spectrum of 10–100 Hz (Fig. 3).

This current was used in reference to a study which found positive effects of a white-noise-like electrical stimulation on balance control (Kimura and Kouzaki, 2013). Electrodes were placed under the hallux and the proximal aspects of the metatarsal heads to stimulate MET I (Fig. 4a). To stimulate the area around the heel, electrodes were placed at the Achilles tendon above the posterior edge of the calcaneus and under the distal area of the plantar calcaneus (Fig. 4b).

2.4.2. Vibration-group (Vi-G)

Mechanical stimulation in Vi-G was performed directly at the two anatomical locations using the vibration exciter (Fig. 4). The mechanical stimulation signal was adapted to the electrical stimulation signal through a self-written LabVIEW (National Instruments, Austin, USA) program. The signal curve of the mechanical stimulation signal, applied with the vibration exciter, was the same (frequency spectrum & pause times) as shown for the electrical stimulation signal in Fig. 3.

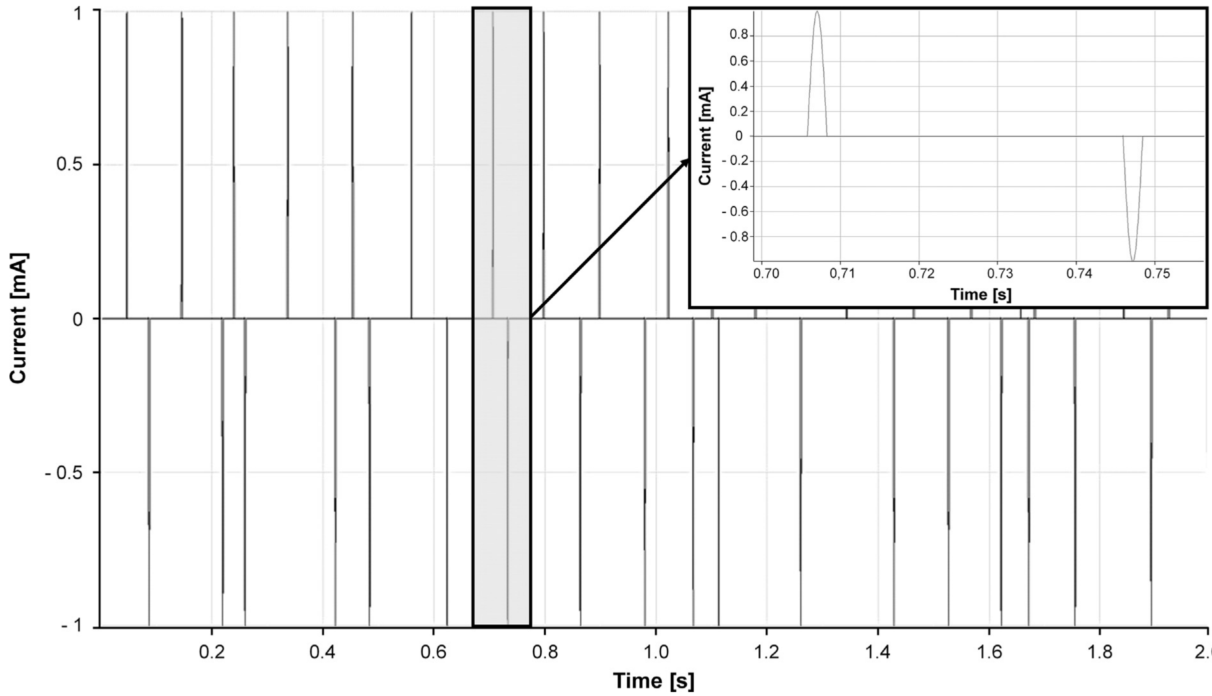

Fig. 3. Extract (2 s) from the signal-time curve of the stochastic biphasic current. The normal graphic shows the randomized pause times (10–100 ms) between the pulses. The zoomed graphic shows the short triangular pulses of 1 ms duration.

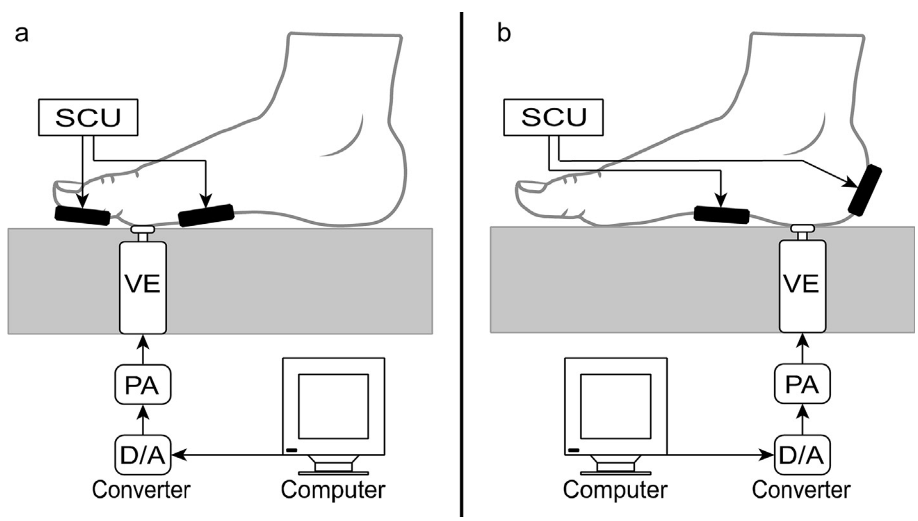

Fig. 4. Intervention at the first metatarsal head (a) and heel (b) for the current group (Cu-G) and placebo-current group (Pl-Cu). In contrast to the current groups, intervention for the vibration group (Vi-G) and placebo-vibration group (Pl-Vi) was without electrodes and stimulation current unit (SCU) directly at the two anatomical locations. VE: vibration exciter; PA: power amplifier; D/A Converter: digital to analogue converter.

2.4.3. Threshold determination for the intervention

The estimation of thresholds on both anatomical locations was carried out separately, based on individual perception. The electrical or mechanical stimulation was raised in steps of 0.5 mA (for electrical stimulation) or 0.05 V (for mechanical stimulation) from zero up to the point at which the subjects felt a slight tingle. Stimulation duration was two seconds and the subjects should press a button as soon as they felt any kind of stimulation. This level signal was defined as the individual perception threshold. In both intervention groups, the mean out of three perception thresholds was used to calculate the stimulation intensity of 90% of the individual perception threshold (Cloutier et al., 2009; Khaodhiar et al., 2003; Liu et al., 2002). Before intervention, subjects were asked if they felt the calculated 90% individual perception threshold. If so, the intensity was reduced according to the protocol.

2.4.4. Placebo-current group (Pl-Cu) and placebo-vibration group (Pl-Vi)

Both placebo groups underwent exactly the same intervention procedure as Vi-G and Cu-G (including the threshold determination for the intervention). However, there was no electrical or mechanical stimulation during the five minute intervention. The subjects of the two placebo groups were blinded to the intervention. After the measurement procedure, participants were informed that the intervention in their case was only mock.

2.4.5. Control-group (Co-G)

The Co-G is the only group that received no intervention at all. To maintain similar conditions to the other groups, subjects in Co-G stood for five minutes.

2.5. Statistical analysis

IBM SPSS Statistics 25 was used for statistical analysis (International Business Machine Corporation (IBM), Armonk, USA). With regard to the great individuality of the sensory system, we removed outliers prior to the statistical evaluation. Based on Strzalkowski et al. (2015), outliers defined as three times the standard deviation were removed ($n = 8$). Subsequently, the data from 91 subjects were subjected to analysis. Since sensory data are recorded on a ratio scale, they lead to heteroscedastic errors (Nevill and Atkinson, 1997). To correct heteroscedasticity and the non-normality distribution, data were transformed with the natural logarithm (Mildren et al., 2015; Nevill and Atkinson, 1997). While the heteroscedasticity could be eliminated, not all parameters were distributed normally after transformation. Therefore, parametric and non-parametric tests were used.

To check whether there were differences between the measurement conditions (BASE, PRE and POST), a repeated measures ANOVA (or Friedman test) was performed. To determine whether VPTs differed between groups within a measurement condition, a one-way variance analysis (or Kruskal-Wallis test) was used. Intervention-related effects between the measurements were investigated using t-tests for dependent variables (or Wilcoxon signed-rank test). Significant results were Bonferroni corrected in the context of the ANOVA (or Friedman test), and alpha was set at $p < 0.05$. For the t-tests (and Wilcoxon tests), the level of significance was corrected to alpha = 0.05/5 = 0.01 due to the number of the groups ($n = 5$).

3. Results

There were no age differences between the individual groups (Chi square(2) = 4.760, $p = 0.313$, $n = 91$) and plantar temperature was within acceptable ranges (Schlee et al., 2009). All tables and figures display raw values. The repeated measures ANOVA (MET I, Greenhouse-Geisser, $F(1.806,162.569) = 8.418$, $p = 0.001$, $\eta^2 = 0.086$, $n = 91$) and Friedman test (Heel, Chi square(2) = 18.549, $p < 0.001$, $n = 91$) revealed significant main effects for the measurement conditions. Pairwise analysis showed no significant differences between BASE and PRE for either anatomical location. However, highly significant differences were found for the heel and MET I between BASE and POST, as well as PRE and POST (Fig. 5).

Table 1 shows the results for VPTs after the described five-minute intervention for each group and the two anatomical locations.

Significantly higher values under the heel (Chi square(4) = 9.729, $p = 0.045$, $n = 91$) were found for Vi-G when compared to Pl-Cu ($z = 2.534$, $p = 0.011$) and Co-G ($z = 2.614$, $p = 0.009$) after intervention. Furthermore, post-hoc analysis revealed that the vibration threshold under the heel (BASE vs. POST, *t*-test: $t = -4.389$, $p < 0.001$, $n = 22$; PRE vs. POST, Wilcoxon-Test: $z = -3.620$, $p < 0.001$, $n = 22$) and MET I (BASE vs. POST, Wilcoxon-Test: $z = -2.581$, $p = 0.01$, $n = 22$) after intervention were significantly higher for Vi-G. All other groups showed no significant differences (Table 1).

4. Discussion

The aim of the present study was to investigate the effects of subliminal electrical and mechanical stimulation on vibration perception thresholds of the sole of the foot of healthy elderly subjects. We hypothesized that subliminal electrical and mechanical noise - applied to the sole of the foot of healthy elderly subjects - improves vibration perception thresholds.

Overall, we found no significant differences between the subject groups within BASE and PRE-conditions. Furthermore, we analyzed increased VPTs after the intervention for both anatomical locations, which means sensory perception was impaired. This increase revealed only one statistically significant difference, namely in Vi-G (Table 1). Contrary to the literature, this implies that the mechanical stimulation in Vi-G leads to a deterioration of the VPTs (Cloutier et al., 2009; Dhruv et al., 2002; Khaodhiar et al., 2003). This result was confirmed by significant differences under the heel between Vi-G (POST) when compared to Pl-Cu and Co-G, which did not receive an intervention at any time. Based on these results, we have to reject our hypothesis. Neither subliminal mechanical nor electrical stimulation improved VPTs in the current study.

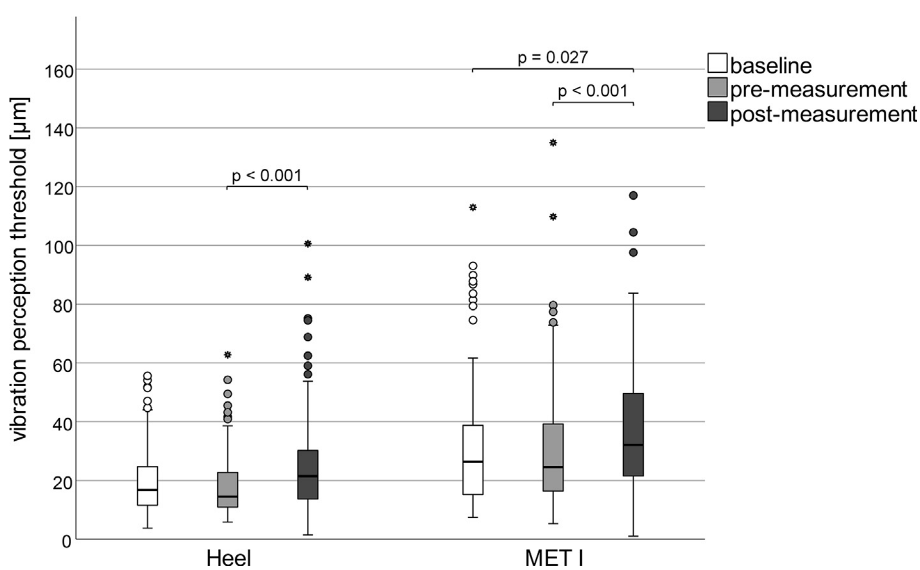

Fig. 5. Results of the repeated measures ANOVA and Friedman test over all subjects ($n = 91$) for the heel and the first metatarsal head (MET I). Circles describe outliers that occur in the interquartile range (IQR) of $x_{0.75}$ + 1.5 IQR and $x_{0.75}$ + 3 IQR. Asterisks describe extreme values above the IQR of $x_{0.75}$ + 3 IQR. The error bars represent the standard deviation.

Table 1
Vibration perception thresholds for each group and anatomical location.

n = 91 (adjusted)	Heel [μm]			MET I [μm]		
	BASE	PRE	POST	BASE	PRE	POST
VPTs Vi-G [n = 22]	$17.8 \pm 13.2^{\$}$	$16.4 \pm 13.1^{*}$	$31.8 \pm 19.6^{\$*\S\#}$	$26.5 \pm 24.9^{\circ}$	25.5 ± 16.4	$39.3 \pm 24.1^{\circ}$
VPTs Cu-G [n = 24]	23.9 ± 13.9	22.3 ± 12.3	27.6 ± 21.6	37.7 ± 22.1	37.0 ± 28.6	42.0 ± 20.9
VPTs Co-G [n = 22]	20.7 ± 10.5	17.0 ± 8.0	$20.5 \pm 14.5^{\S}$	34.4 ± 22.5	31.4 ± 20.8	38.7 ± 27.7
VPTs Pl-Vi [n = 10]	20.5 ± 7.8	23.0 ± 11.7	22.7 ± 9.2	34.8 ± 23.5	27.9 ± 18.4	39.2 ± 20.1
VPTs Pl-Cu [n = 13]	16.6 ± 10.8	15.9 ± 11.1	$20.6 \pm 17.8^{\#}$	30.1 ± 22.4	30.3 ± 23.0	34.5 ± 28.0

Mean ± SD of vibration perception thresholds (VPTs) for each condition (BASE, PRE and POST) and for both anatomical locations (heel and first metatarsal head, MET I) for each group: vibration (Vi-G), current (Cu-G), control (Co-G), placebo vibration (Pl-Vi), and placebo current (Pl-Cu). Superscripted symbols represent significant differences.

Changes occurred only in Vi-G, and even led to a deterioration of VPT. Vi-G was the only group that underwent a five-minute mechanical stimulation while standing. During stimulation, Vi-G stood on the anatomical position above the metal probe of the vibration exciter, and the vibration perception threshold was measured directly afterwards (Fig. 4). This increased mechanical stress (increased pressure + subliminal mechanical stimulation) may have led to receptor adaptations, meaning higher VPT in the POST condition. Studies show that the fast-adapting mechanoreceptors (Meissner and Pacinian Corpuscles) adapt to extended suprathreshold vibrations (Bensmaïa et al., 2005; Leung et al., 2005). The degree of adaptation depends essentially on the amplitude of the adaptation stimulus (Bensmaïa et al., 2005). In relation to the standing position of Vi-G and the 2 mm protruding metal probe, it can be assumed that the adaption stimulus in our study was relatively strong. Bensmaïa et al. (2005) and Leung et al. (2005) attribute the receptor adaptations to an increased influx of calcium ions, which significantly influence the transduction process. The increased calcium enrichment leads to an increase in the spiking threshold and thus to a shift in threshold values (Bensmaïa et al., 2005). Once the adaptation stimulus is over, the receptor needs up to 16 min to return to its resting sensitivity (Leung et al., 2005).

The above described studies on possible adaptation effects refer to suprathreshold vibration stimuli. The theory behind noise intervention is that the randomness of subliminal noise signals is intended to avoid adaptation of the receptor. Similar to Kimura and Kouzaki (2013), we used a stochastic signal which consists of short triangular pulses with a duration of 1 ms. A micro-electric random generator varies the pause times between the pulses within 10–100 ms. Therefore, a random stimulus pattern is created in a frequency spectrum of 10–100 Hz (Fig. 3). Instead, the second long-term exposure - pressure - seems to have caused a receptor adaptation. Chung et al. (2015) demonstrate cortical adjustments in relation to sustained pressure stimulation for slowly adapting type I mechanoreceptors. As little as simple static pressure of 15 s led to lower activity in high-level tactile perceptual processes, which may lead to a decay of the transmission of tactile information to stimulus localization in the somatosensory cortex over time (Chung et al., 2015). The rapidly adapting Meissner Corpuscles addressed in our study normally do not adjust their ability to respond based on constant pressure. However, to our knowledge, there are currently no studies on long-term pressure adaptation in rapidly adapting mechanoreceptors. Considering the refractory time of a receptor of up to 16 min on extended suprathreshold vibrations (Leung et al., 2005), comparably long refractory times with respect to sustained pressure seem possible. Future studies should examine this assumption in more detail.

We presume that the receptors were fatigued by the subliminal mechanical vibration (Barker et al., 1982; Catton, 1970). Catton (1970) defines fatigue 'as the rise of threshold that occurs during repetitive stimulation with brief mechanical pulses' (p. 301). There are three variables that mainly influence the magnitude of fatigue: duration, interstimulus interval, and amplitude (Barker et al., 1982). In our study, the amplitude was 90% of the individual perception threshold for a five-minute intervention. Compared to the study by Barker et al. (1982), the duration of our stimulation was longer and the interstimulus interval was faster, which could have led to increased fatigue. Since the rate of fatigue is a function of the frequency stimulation (the faster the signal, the greater the fatigue), it is clear that the recovery of excitability requires several minutes (Catton, 1970).

Furthermore, we found no improvement in VPT after electrical intervention. A previous study has shown that suprathreshold transcutaneous electrical stimulation does not affect mechanical thresholds (Klöcker et al., 2016). The authors attribute this to the fact that the input generated by the electrical stimulus is not limited to a certain category of sensory afferents and therefore does not induce adaptation at the level of the central nervous system (Klöcker et al., 2016). Since we have used subliminal electrical stimuli, this result may be expected. Furthermore, the effect of electrical stimulation may only be effective if it is stimulated simultaneously with sensitivity testing (Dhruv et al., 2002; Iliopoulos et al., 2014; Richardson et al., 1998).

We did not use (Gaussian) white noise, since pilot tests using mechanical Gaussian white noise have shown that the white noise adjustment to a real subliminal 90% noise intensity results in a considerably low stimulus signal. As long as the signal is not limited by the Gaussian distribution, it is always possible to generate perceivable amplitude peaks. However, no methodological information is given in the relevant literature (Collins et al., 1997; Cordo et al., 1996; Iliopoulos et al., 2014; Liu et al., 2002; Richardson et al., 1998; Wells et al., 2005). By adapting the mechanical signal to the electrical signal, we aimed to ensure that both forms of stimulation could be compared with each other. Since our current device increased in steps of 0.5 mA (device limitation), we could not always stimulate with exactly 90%. During electrical stimulation, an average intensity of 82.4 ± 8.5% (minimum 53.3%, maximum 90%) for the heel and 86.7 ± 3.6% (minimum 75.0%, maximum 92.3%) for MET I was applied. Mechanical stimulation could be adjusted more precisely with steps of 0.05 V. The average intensity was 87.1 ± 6.7% (minimum 62.5%, maximum 90.0%) for the heel and 87.5 ± 3.8% (minimum 76.8%, maximum 90.0%) for MET I. Nevertheless, our stimulation was subliminal and individually adapted to each subject at any time. Studies have also shown that even subliminal stimulation below 90% intensity can improve balance and sensitivity (Dhruv et al., 2002; Magalhães and Kohn, 2012).

Furthermore, mechanical noise primarily acts on the receptors themselves while electrical noise stimulation directly modulates the nerve fiber (Iliopoulos et al., 2014). This results in two different effects on the somatosensory system, which may cause a different mode of stimulation (Iliopoulos et al., 2014). In this context, Wells et al. (2005) described a band-pass filter for their mechanical noise to only stimulate the relevant FAI (0.125–50 Hz) or FAII (50–500 Hz) mechanoreceptors. In our study, we examined the effects of mechanical or electrical stimulation on FAI-mediated Meissner Corpuscles (VPT measurement with 30 Hz). It is possible that our frequency range of 10–100 Hz also stimulated FAII-mediated Pacinian Corpuscles (optimal vibration response between 100 and 300 Hz (Treede, 2007, p. 307)), which could have confounded thresholds or priming effects on the FAI receptors (Wells et al., 2005). On the other hand, for electrical noise stimulation, stochastic resonance effects can best be achieved when noise is faster than the target signal (Iliopoulos et al., 2014). Our target signal was a 30 Hz vibration, which lies completely within the range of our stimulation frequency of 10–100 Hz. Our current characteristics are based on the study by Kimura and Kouzaki (2013). They used a frequency range of 5–1000 Hz, which were faster than our target signal. However, our bandwidth was limited by our technical requirements.

Vibration perception measurements represent subjective measurements. The subjects' sensation cannot be verified, whereas the success of the measurements depends to a large extent on the subjects' cooperation. To maintain high subject concentration levels, we took several breaks for recovery. Nevertheless, individual measurement bias can be attributed to possible concentration fluctuations. However, a very good reproducibility between all measuring conditions was observed for all groups (with exception of Vi-G) (Table 1). The changes that occurred in Vi-G after intervention were debated in detail above.

Furthermore, subjects could only participate in the study if none of the exclusion criteria were met as determined through a medical screening. Even though the subjects were free of any diseases that influence the sensory system, pre-diagnosis effects cannot be completely excluded. For example, ophthalmic diseases can represent the endpoint of systemic changes, but these often start slowly and remain undetected for a long time. For this reason, future studies should explicitly include ophthalmic diseases in the exclusion criteria.

5. Conclusion

Our results do not confirm positive effects of subliminal electrical or of mechanical stimulation on the sole of the foot. Further studies should use different stimulation modalities for electrical and mechanical stimulation, as suggested by Iliopoulos et al. (2014). Although the modalities of (Gaussian) white noise have not yet been fully clarified, future studies should refer to this proven signal form. Additionally, most studies measure tactile sensation while simultaneously stimulating with subliminal noise (Cloutier et al., 2009; Collins et al., 1996, 1997; Dhruv et al., 2002; Iliopoulos et al., 2014; Khaodhiar et al., 2003; Liu et al., 2002; Richardson et al., 1998; Wells et al., 2005). Further studies should focus on this method to quantify the effect of subliminal electrical or mechanical stimulation on the sole of the foot. The results of the present study raise questions regarding the effectivity of fall prophylactics in the elderly, which could be addressed in future studies.

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Disclosures

The authors declare that there are no conflicts of interest.

Author contributions

C.Z., L.N., K.K.: participated in the design of the study, performed experiments; C.Z.: analyzed data, drafted the manuscript, designed figures; C.Z., L.N., K.K. T.M.: edited and revised the manuscript and data analysis; T.M. participated in the design of the study. All authors read and approved the final manuscript.

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