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Subthreshold white noise vibration alters trembling sway in older adults

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ABSTRACT

Background: Somatosensory deficit is a significant contributor to falls in older adults. Stochastic resonance has shown promise in recent studies of somatosensation-based balance disorders, improving many measures of stability both inside and outside of the clinic. However, our understanding of this effect from a physiological perspective is poorly understood. Therefore, the primary goal of this study is to explore the influence of subthreshold vibratory stimulation on sway under the rambling-trembling framework.
Methods: 10 Healthy older adults (60–65 years) volunteered to participate in this study. Each participant underwent two randomized testing sessions on separate days, one experimental and one placebo. During each session, the participants' baseline sway was captured during one 90-s quiet standing trial. Their sensation threshold was then captured using a custom vibratory mat and 4–2-1 vibration perception threshold test. Finally, participants completed another 90-s quiet standing trial while the vibratory mat vibrated at 90% of their measured threshold (if experimental) or with the mat off (if placebo). While they completed these trials, an AMTI force plate collected force and moment data in the anteroposterior (AP) and mediolateral (ML), from which the center of pressure (COP), rambling (RM), and trembling (TR) time series were calculated. From each of these time series, range, variability (root-mean-square), and predictability (sample entropy) were extracted. One-tailed paired *t*-tests were used to compare baseline and during-vibration measures.
Results: No significant differences were found during the placebo session. For the experimental session, significant increases were found in AP TR range, ML TR RMS, AP COP predictability, and AP & ML TR predictability. The TR time series was particularly sensitive to vibration, suggesting a strong influence on peripheral/spinal mechanisms of postural control.
Significance: Though it is unclear whether observed effects are indicative of "improvements" or not, it does suggest that there was a measurable effect of subthreshold vibration on sway. This knowledge should be utilized in future studies of stochastic resonance, potentially acting as a mode of customization, tailoring vibration location, duration, magnitude, and frequency content to achieve the desired effect. One day, this work may aid in our ability to treat somatosensation-based balance deficits, ultimately reducing the incidence and severity of falls in older adults.

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1. Introduction

As the leading cause of injury among individuals aged 65 and older, accidental falls present a substantial and ongoing threat to older adults (Bergen, Stevens, & Burns, 2016). Healthy aging introduces a myriad of physiological changes that limit the body's ability to assess its position in space and respond to perturbations. Among these changes is an increased sensory threshold, in which a progressively greater magnitude of stimuli is required to achieve sensation (Lipsitz et al., 2015; Perry, 2006; Speers, Kuo, & Horak, 2002; Wickremaratchi & Llewelyn, 2006). This dampening of the senses is a significant contributor to falls in older adults, limiting the reliability of somatosensory input required to maintain balance.

Somatosensory decline, as seen in healthy aging, is thought to decrease physiologic complexity, a vital attribute of robust, stable balance (Lipsitz, 2002; Manor & Lipsitz, 2013; Vaillancourt & Newell, 2002). Decreasing sway complexity can result in behavior that is either too random or too repetitive, both of which are associated with increased fall risk in older adults and those with balance disorders, such as Parkinson's Disease (Stergiou, Harbourne, & Cavanaugh, 2006). In quiet standing, age-related declines in complexity often manifest as increased magnitude, variability, and predictability of the center-of-pressure (Costa et al., 2007; Roman-Liu, 2018; Zhou, Lipsitz, Habtemariam, & Manor, 2016). Such behavior is indicative of sway that is exceedingly repetitive, largely unstable, and presents a high degree of fall risk.

Treatment options for those suffering from somatosensory loss are extremely limited, but stochastic facilitation has the potential to recover this loss in sensation and subsequent complexity. The phenomenon of stochastic resonance has been observed in a wide variety of populations, from children with cerebral palsy to older adults and those with diabetic peripheral neuropathy, using noise to enhance pre-existing tactile signals in the environment (Bagherzadeh Cham et al., 2018; Costa et al., 2007; Dettmer, Pourmoghaddam, Lee, & Layne, 2015; Hijmans, Geertzen, Zijlstra, Hof, & Postema, 2008). This effect is noted as a phenomenon because the exact mechanism has yet to be fully explained, but researchers suggest that this effect is achieved through the augmentation of environmental stimuli, boosting existing signals to levels perceivable by individuals with heightened sensory thresholds (Bagherzadeh Cham et al., 2018; Zhou et al., 2016).

However, this proposed effect is not well documented, especially within the rambling-trembling framework, an analytical method that decomposes the center of pressure into large-scale movement of an equilibrium point and oscillations around this point (Lipsitz et al., 2015; Stania et al., 2020; Wang, Watanabe, & Chen, 2016; Wuehr et al., 2018; Zatsiorsky & Duarte, 1999). Thus, the primary goal of this study is to assess the influence of vibrotactile stochastic facilitation on the improvement of physiologic complexity in the aging population. Additionally, although the proposed mechanism of stochastic facilitation aligns with its observed effects, the exact mechanism is not fully understood (McDonnell & Ward, 2011; Viseux et al., 2019; Zarkou, Lee, Prosser, Hwang, & Jeka, 2018). Therefore, the secondary goal of this study is to provide insight into the mechanism of action of vibrotactile-based stochastic facilitation with respect to the individual contributions of rambling and trembling components of the center of pressure. Based on these goals, it was hypothesized that (1) subthreshold vibration will decrease system (1.a) magnitude, (1.b) variability, and (1.c) predictability (increase SampEn), and (2) the TR time series will show more prominent changes to sway compared to COP and RM time series, demonstrated by the number of significant differences.

2. Materials and methods

2.1. Participants

Ten healthy older adults (aged 62.8 $\pm$ 1.6 years, 7 female) volunteered to participate in this study. All participants were informed of the study risks and benefits and provided written consent, as approved by the University of Kansas Institutional Review Board. Participants with a history of neurological disorder, balance impairment, and/or significant injury to the trunk or lower limbs were excluded from the study.

2.2. Vibratory mat

The tests conducted in this study required subjects to stand on a custom-made vibrating mat. This mat was composed primarily of Shore A50 silicone, with three embedded eccentric rotating mass motors (307–103, Precision Microdrives, London, UK) beneath each foot, positioned approximately at the heel, the first metatarsal, and the fifth metatarsal. The mat measures 0.5 m $\times$ 0.4 m $\times$ 13 mm. The motors were placed using a standardized stance width (17 cm) and angle (14° between the feet) (McIlroy & Maki, 1997). The motors are powered by a 5-V and 12-V external power supply. They are controlled with DRV2605 chips (Texas Instruments, Dallas, TX, USA) and custom-built Arduino (Arduino, Somerville, MA, USA) code. The motors output white noise vibration, as validated in previous work (Giraldo, 2021). The mat was placed atop a 6-axis AMTI force plate (Watertown, MA, USA).

2.3. Testing conditions

Participants completed two testing sessions (stimulation and placebo) in a randomized order on separate days. Testing sessions were structured identically and had three primary tests: (1) baseline sway, (2) sensation threshold determination, and (3) stimulation sway, as shown in Fig. 1. The baseline sway trial was performed prior to exposure to vibratory stimuli of any kind. Participants stood quietly, barefoot, on the vibratory mat (with motors off) for 90 s with their feet aligned to the standardized stance width and angle and eyes closed to eliminate the effects of visual compensatory strategies.

To determine the sensory threshold, subjects then stood on the mat and completed a modified 4–2-1 vibration perception threshold (VPT) test developed by Whorley and colleagues (2020), which calculates the individual's threshold as a percentage of the maximum motor output magnitude (Dyck, 1993; Whorley, 2020). Briefly, this method uses subject-initiated feedback and increments of progressively shrinking vibration magnitude to hone in on an individual's vibration perception threshold. The original 4–2-1 VPT methodology by Dyck (1993) was modified per Whorley (2020), including three key changes to test implementation:

(1) Subject familiarization: prior to commencing the modified 4–2-1 VPT test, subjects were exposed to a brief, 10-s period of suprathreshold vibration to promote sensory awareness and preparation of the participant. Following a brief pause, threshold determination then began at the same stimulus magnitude. For many, vibration at the plantar surface is a novel sensation, so this change sought to eliminate any learning period associated with the administration of vibration.
(2) Double-blinded instantaneous subject feedback: the modified 4–2-1 VPT test utilized a manual push-button, given to the subjects during the test, to indicate when they did or did not feel vibration. Participants were instructed to press and hold the button when they felt vibration and release when they did not. This feedback was communicated directly to the data collection computer and fed into the 4–2-1 stepping algorithm. This change removed the need for verbal researcher prompting and aimed to eliminate confounding false positive participant responses (e.g. inadvertently making participants believe that they "should" be feeling vibration).
(3) Standardization of vibration magnitude "step" sizes: Dyck's original 4–2-1 algorithm employed a scale of 25 uneven, participant-specific increments of vibration magnitude. While this may allow for a high degree of accuracy, it is also a lengthy and potentially fatigue-inducing process that could confound threshold calculations, especially in older adults. Instead, the modified 4–2-1 VPT test utilized standardized increments of vibration magnitude to improve test efficiency and reduce any potential fatigue effect, while maintaining high repeatability of threshold determination.

Finally, participants stood quietly with eyes closed on the mat for 90 s; for the stimulation session, the motors administered subthreshold white noise vibration at 90% of their measured threshold (Spielholz, Dyck, O'Brien, Shy, & Frohman, 2003). During the placebo session, participants still stood on the mat for 90 s, but received no stimulation. The session order was randomized and participants were blinded to which session included vibration.

2.4. Data collection and analysis

Foot-floor kinetic data were collected at 100 Hz using the 6-axis AMTI force plate underneath the vibratory mat and a 16-bit A/D acquisition system (Cambridge Electronic Design, Cambridge, UK). Using MATLAB software (Mathworks, Natick, MA, USA), data were filtered with a 4th order 10 Hz low-pass Butterworth filter and down-sampled to 50 Hz. Spectral analysis of frequency content was used to ensure force artifact from motor vibration was filtered out prior to analysis. This data were then used to calculate the COP time series (Winter, Patla, & Frank, 1990). Force and COP time series were then used to calculate RM and TR time series in the AP and ML directions (Zatsiorsky & Duarte, 1999). From these time series, range, root-mean-square (RMS) and sample entropy (SampEn) were extracted. SampEn input parameters of $m = 2$ and $r = 0.1$ were selected based on recommendations from previous work (Nichols, 2020).

2.5. Statistical analysis

Microsoft Excel was used to perform statistical analyses. Descriptive statistics and Jarque-Bera tests were used to evaluate normality of the data distribution. One-tailed, paired *t*-tests were performed to compare differences in sway outcome measures (range, RMS, and SampEn) between baseline and stimulation/placebo sway trials. Significance was set to $p < 0.05$. A statistical power analysis was used to determine minimum sample size for this study. With alpha = 0.05 and power = 80%, the required sample size was

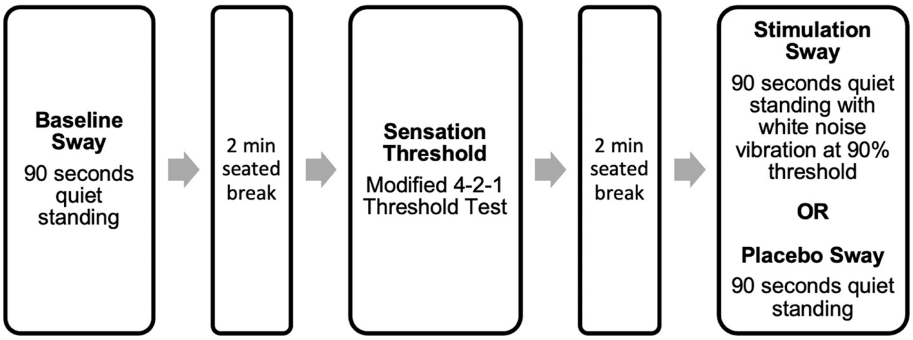

Fig. 1. Protocol flow for each testing session, including (1) baseline sway, (2) sensation threshold determination, and (3) stimulation (or placebo) sway with 2-min seated breaks between trials.

estimated to be $N = 10$ participants.

3. Results

With a large effect size (d = 0.92) and final sample size of 10, post hoc statistical power was calculated to be 81%. The average measured sensation threshold was 45.1 ± 11.0% of the maximum motor power, which corresponds to approximately 2.5 Newtons of vibrational force (Giraldo, 2021). No significant differences were found between baseline and placebo trials. Representative stabilogram plots for COP, RM, and TR components during baseline and stimulation trials are shown in Fig. 2. Differences between baseline and stimulation trials are detailed below.

3.1. Range

Mean range in the anteroposterior (AP) and mediolateral (ML) directions increased in stimulation sway compared to baseline for the COP, RM, and TR time series, with a significant increase ($p = 0.039$) in AP TR range (Fig. 3a-b, Table 1). AP TR range increased between baseline and stimulation trials for 7 out of 10 total participants (Fig. 3).

3.2. Root-mean-square (RMS)

RMS values were comparable in the baseline and stimulation trials in the AP-direction, with no significant differences between trials for COP, RM, or TR (Fig. 3c). In the ML-direction, mean RMS decreased for the COP and RM time series, but not significantly (Fig. 3d). For the TR time series, ML RMS increased from the baseline sway trial to stimulation ($p = 0.024$). For this measure, 7 out of 10 subjects experienced an increase in TR ML RMS (Fig. 3).

3.3. Sample entropy (SampEn)

COP AP SampEn showed a significant decrease ($p = 0.045$) between baseline and stimulation trials (Fig. 3e), but individual differences varied, with 5 subjects increasing and 5 decreasing (Fig. 4). RM showed no significant differences between baseline and stimulation sway SampEn in the AP- or ML-directions. TR showed a significant decrease in SampEn between baseline and stimulation

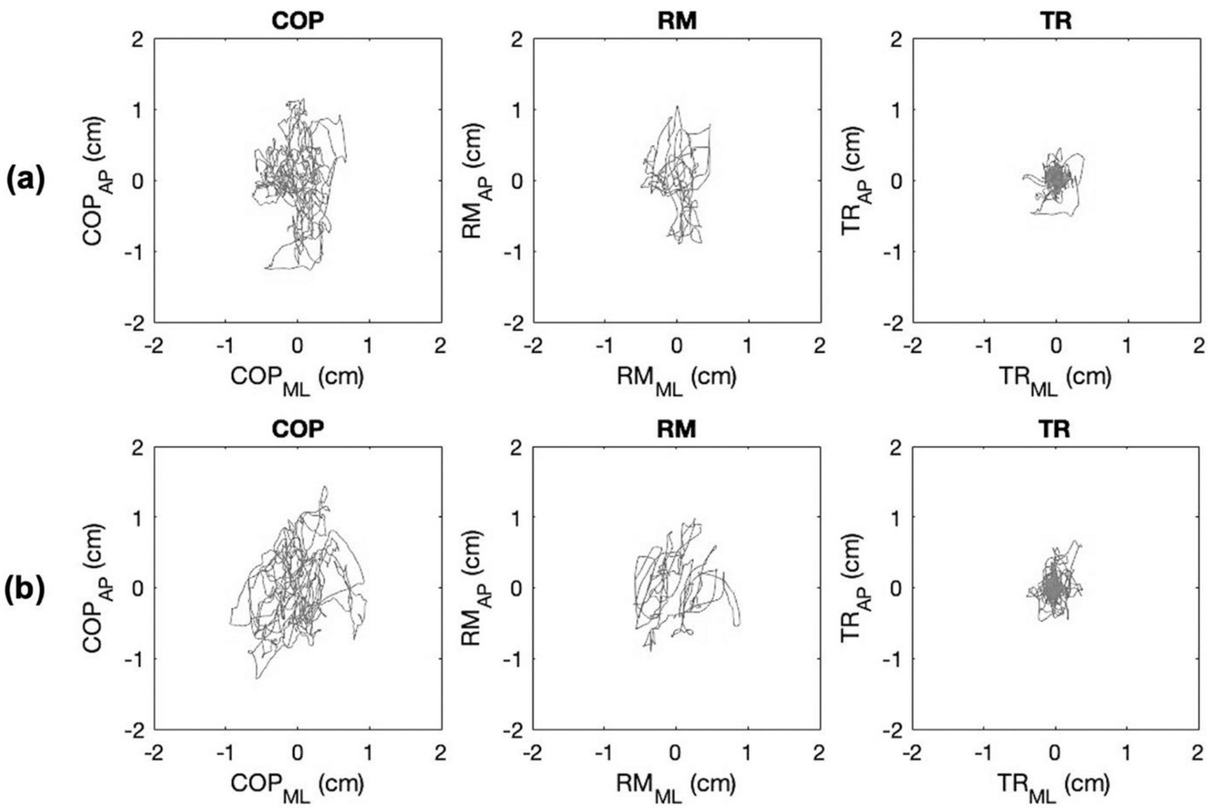

Fig. 2. Representative stabilogram plots for an individual subject, including rambling (RM) and trembling (TR) components for 90-s (a) baseline and (b) stimulation trials.

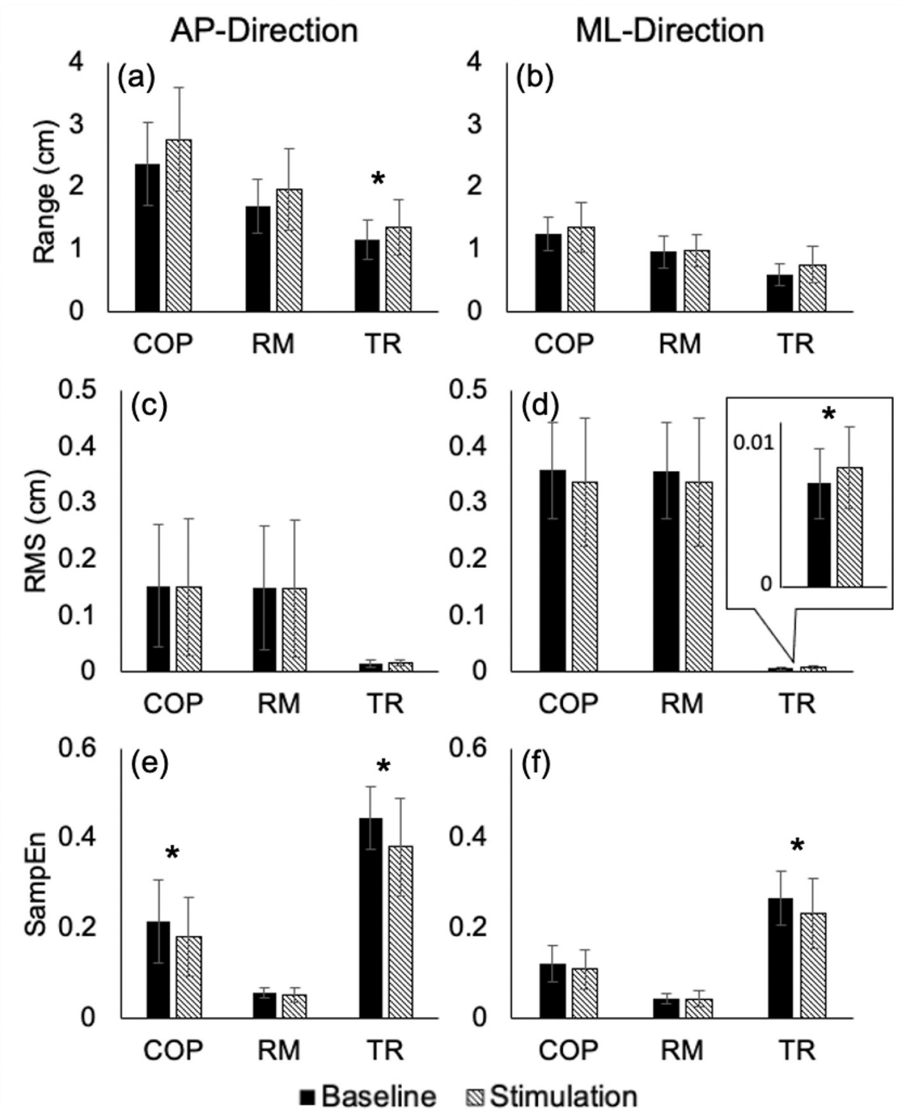

Fig. 3. Mean outcome measures for baseline and stimulation sway trials. Standard deviations are shown with error bars. Significant baseline-stimulation differences ($p < 0.05$) are shown with asterisks (*).

in the AP- ($p = 0.009$) and ML-direction ($p = 0.038$). This decreasing trend in TR SampEn was present in 8 out of 10 and 9 out of 10 total subjects in the AP- and ML-directions, respectively (Fig. 4).

4. Discussion

The primary aim of this study was to explore the effects of subthreshold vibratory stimulation on the center of pressure (COP) and its rambling (RM) and trembling (TR) components. The placebo trials yielded no significant differences to baseline in any sway measure, reinforcing the relationship between observed effects and vibratory stimulation.

There were two main hypotheses in this study: (1) subthreshold vibration will decrease system (1.a) magnitude, (1.b) variability, and (1.c) predictability (increase SampEn) and (2) the TR time series will show more prominent changes to sway compared to COP and RM time series, demonstrated by the number of significant differences.

Sway magnitude is known to increase in aging, covering a larger range of position in both the AP- and ML-direction (Degani, Leonard, & Danna-dos-Santos, 2017; Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996; Roman-Liu, 2018). Contrary to hypothesis 1.a, range increased between baseline and stimulation trials, suggesting that subthreshold white noise vibration was counterproductive to reversing this effect of aging. Sway variability (RMS) also tends to increase in aging (Degani et al., 2017; Prieto et al., 1996). There were no significant differences in RMS between baseline and stimulation in the AP-direction, with near-identical trial means. In the ML-direction, there was a significant increase in TR RMS from baseline to stimulation, despite COP and RM means

Table 1
Mean and standard deviation (SD) of outcome measures for baseline (BL) and stimulation (STIM) sway trials. Significant BL-STIM differences ($p <$ 0.05) are bolded and italicized.

Outcome Measure	Time Series	BL (mean ± SD)	STIM (mean ± SD)	*p*-value
AP Range (cm)	COP	2.384 ± 0.670	2.769 ± 0.828	0.086
	RM	1.691 ± 0.429	1.972 ± 0.653	0.131
	TR	1.157 ± 0.315	1.358 ± 0.443	***0.039***
ML Range (cm)	COP	1.243 ± 0.268	1.356 ± 0.399	0.261
	RM	0.962 ± 0.259	0.985 ± 0.264	0.433
	TR	0.601 ± 0.180	0.748 ± 0.292	0.089
AP RMS (cm)	COP	0.153 ± 0.108	0.151 ± 0.120	0.471
	RM	0.150 ± 0.110	0.149 ± 0.122	0.479
	TR	0.016 ± 0.006	0.017 ± 0.005	0.196
ML RMS (cm)	COP	0.358 ± 0.085	0.337 ± 0.114	0.083
	RM	0.358 ± 0.085	0.337 ± 0.114	0.083
	TR	0.007 ± 0.002	0.008 ± 0.003	***0.012***
AP SampEn	COP	0.217 ± 0.091	0.182 ± 0.182	***0.045***
	RM	0.058 ± 0.012	0.052 ± 0.052	0.194
	TR	0.446 ± 0.070	0.382 ± 0.382	***0.005***
ML SampEn	COP	0.122 ± 0.042	0.109 ± 0.109	0.176
	RM	0.045 ± 0.012	0.045 ± 0.045	0.476
	TR	0.268 ± 0.060	0.235 ± 0.235	***0.019***

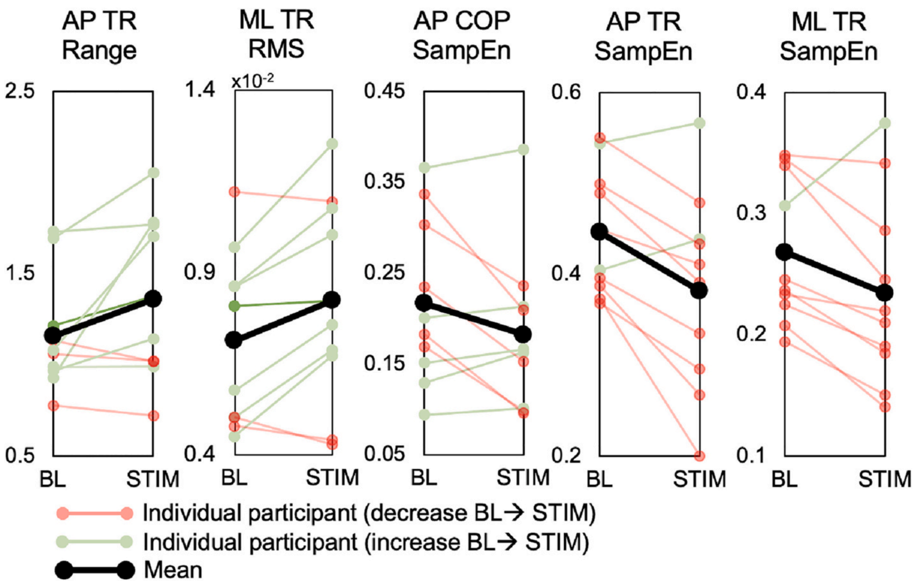

Fig. 4. Baseline (BL) and stimulation (STIM) trial values for individual participants in selected outcome measures. Measures selected include only those found to have a significant difference between BL and STIM trials, as determined by paired *t*-tests.

trending downward (albeit insignificantly). The decreasing trend observed in COP and RM loosely supports hypothesis 1.b, but the significant increase in TR does not align with this conclusion. Results of this study do not support hypothesis 1.c, which stated that vibratory stimulation would decrease predictability, exhibited by significant decreases in SampEn (increases in predictability) from baseline to stimulation for AP COP and AP and ML TR.

Stochastic facilitation has been shown beneficial in studies with older adults (Lipsitz et al., 2015; Stephen et al., 2012), individuals with diabetic peripheral neuropathy (Bagherzadeh Cham, Mohseni-Bandpei, Bahramizadeh, Kalbasi, & Biglarian, 2016; Hijmans et al., 2008), stroke survivors (Karimi-AhmadAbadi, Naghdi, Ansari, Fakhari, & Khalifeloo, 2018; Priplata et al., 2006), and athletes (Miranda et al., 2016). These benefits have been demonstrated in a multitude of experimental methods, including center-of-pressure and gait analyses, plantar pressure distribution, clinical evaluations of spasticity and range of motion, agility tasks, and direct assessment of sensation threshold (Bagherzadeh Cham et al., 2018; Chen et al., 2020; White, Johannsen, Goswami, Trenado, & Babič, 2019; Zwaferink et al., 2020). Despite this promise, findings of this study do not directly support the previously-reported benefits of stochastic facilitation.

However, these conflicting results are more likely a reflection of the immense variability in methods between studies, rather than a cause for concern regarding the efficacy of stochastic facilitation. The present study utilized a custom vibratory mat and modified 4–2-

1 VPT protocol to establish the individual's subthreshold vibration magnitude, inspired by previous work, with 6 motors embedded at the approximate location of three major bony landmarks in each foot (Dyck, 1993; Kavounoudias, Roll, & Roll, 1998, 1999; Whorley, 2020). But vibration has been applied in many different ways that have undoubtedly contributed to discrepancies in the observed effects between studies. It is possible that varying conditions, such as stimulation location, duration, magnitude, and frequency content of vibration, induce unique sway responses.

Additionally, our results further elucidate inconsistencies in the literature regarding observed trends in nonlinear COP analysis in aging. In this study, it was hypothesized that vibration would decrease predictability (increase SampEn). Though not tested directly, it was assumed that older individuals tend to have lower motion complexity, and therefore predictability. This assumption was based on Lipsitz & Goldberger's Loss of Complexity Hypothesis, which states that a loss of physiological complexity contributes to many negative characteristic effects of aging, making these systems less robust and adaptable (Lipsitz & Goldberger, 1992). Since the emergence of nonlinear methodology, researchers have attempted to quantify this complexity through measures such as sample, approximate, and multiscale entropy, stating that an increase in predictability (or regularity) indicates lower complexity. However, predictability and complexity are not synonymous, and thus observed effects of aging and disease, with respect to entropy, are inconsistent across studies (Goldberger, Peng, & Lipsitz, 2002; Vaillancourt & Newell, 2002). For example, Duarte & Sternad (2008) and Degani et al. (2017) report higher entropy values in older adults compared to healthy young adults, indicating a positive change in our reported results. At the same time, Costa et al. (2007), Manor and Lipsitz (2013), and Roerdink et al. (2006) find lower entropy values, compared to healthy counterparts, in older adults, those experiencing visual and/or somatosensory impairment (like that seen in older adults), and individuals recovering from stroke, respectively (Costa et al., 2007; Manor & Lipsitz, 2013; Roerdink et al., 2006).

Findings from this study simultaneously highlight the potential benefits and underscore the current limitations of both stochastic facilitation and the nonlinear methods used to assess its efficacy. Subthreshold white noise vibration showed seemingly counterproductive effects on sway range, variability, and predictability, but it is unclear whether this is due to vibration settings, assumptions about aging, or true negative consequences of the vibration. It is also uncertain whether existing assumptions about changes in outcome measures that typically signify balance "health" (i.e. decreasing range and RMS or increasing SampEn) are truly indicative of positive change when considering independent RM and TR components (Degani et al., 2017; Maki & McIlroy, 1996).

It is also important to note that, although participants in this study were considered older (aged 60–65 years), it is possible that they were too young to experience many substantial age-related somatosensory declines, more closely resembling their younger counterparts rather than someone in their 70's or 80's. Measured vibration perception thresholds for this 60–65 year old group (45% motor power, ~2.5 N force) were considerably higher than previously measured thresholds for healthy young adults, aged 18–34 years (24% motor power, ~1 N force), but it is predicted that the sensory degradation that occurs beyond 65 years would impose even greater increases in threshold and amplify (or otherwise alter) observed sway effects (Giraldo, 2021; Whorley, 2020). Indicators of balance health improvement from stochastic facilitation are largely dependent on the initial state, as a product of aging and/or pathology (Priplata et al., 2002, 2006; Stergiou et al., 2006). Additionally, the present study sought to target and isolate vibration's effect on the somatosensory system by utilizing eyes-closed testing conditions. The effects of visual input are well-documented in the literature, with a lack of vision greatly increasing measures of postural instability, such as center of pressure path length, sample entropy, and sway velocity (Gaerlan, Alpert, Cross, Louis, & Kowalski, 2012; Richardson & Ashton-Miller, 1996; Strang, Haworth, Hieronymus, Walsh, & Smart, 2011). In fact, it is also understood that many older adults demonstrate a preference for visual input over other sources, often disregarding the vestibular and somatosensory senses. While vision and the process of sensory re-weighting provide valuable insight into the study of postural control, these adaptations are tangential to the goals of the present work. However, postural sway studies in future clinical applications should consider the integration of all available senses and potential sensory re-weighting that may occur as a result of this intervention. Therefore, it is imperative that future clinical work on postural sway includes a variety of sensory conditions (eyes-open and eyes-closed) and samples from populations of older individuals (65+) and specifically those experiencing somatosensory-linked balance disorders, such as diabetic peripheral neuropathy, to fully understand the effects of such an intervention on the people that may benefit the most.

The second hypothesis, which stated that the TR time series would show the most prominent changes with vibration, is supported, as demonstrated by the number of significant differences between baseline and stimulation trials. Of the six measures utilized in this study (range, RMS, and SampEn in the AP and ML directions), four were found to be significantly different from their respective baseline TR values. Meanwhile, the COP time series found only one significant difference (AP SampEn) and the RM time series identified none. The implications of this finding are especially intriguing when considering the hypothesized physiological link between postural control and these rambling and trembling components of sway.

Zatsiorsky and Duarte developed rambling-trembling decomposition as a method of distinguishing two contributions to sway: large-scale movement of an equilibrium point and oscillations around that point (Zatsiorsky & Duarte, 1999). Some researchers have taken this concept several steps further and propose that rambling and trembling components of the COP represent centrally (supraspinal) and peripherally (spinal) controlled movement, respectively (Bolbecker et al., 2018; Shin, Motl, & Sosnoff, 2011; Shin & Sosnoff, 2017; Tahayori, Riley, Mahmoudian, Koceja, & Hong, 2012). Under this framework, our findings suggest that stochastic facilitation may most directly impact oscillatory motion and peripheral control mechanisms of postural control, leaving the ability to establish (and adjust) the equilibrium point relatively unaffected.

Though the measured effects of vibration in this work could be endlessly debated as "good" or "bad," one conclusion can be agreed upon: there was in fact an effect. Subthreshold white noise vibration produced a sharp contrast between COP, rambling, and trembling components, with trembling sway (and its proposed underlying peripheral drivers) showing the most prominent changes with stochastic facilitation. Consequently, this type of intervention may be most beneficial applied on a case-by-case basis, tuning attributes such as vibration location, duration, magnitude, and frequency content to achieve the desired effect; suprathreshold (above-threshold, perceivable) vibration, for example, may more directly target the rambling component as opposed to trembling. Of course, further work must be done to understand the differing influence of these factors before developing such a targeted approach.

5. Conclusions

These results demonstrate the ability of vibration-based stochastic facilitation to induce quantifiable changes to postural sway. Although there remains much to learn with regard to the interpretation and optimization of this effect, subthreshold white noise vibration elicited measurable differences to the trembling component of the center of pressure, modulating the magnitude, variability, and predictability of oscillatory sway motion. Findings from this study may be used to inform future work that seeks to implement stochastic facilitation in older adults and those with clinical balance deficits. Ultimately, this work may aid in the reduction of fall-related injuries and deaths, maintenance of physical mobility and improvement of overall quality of life in aging.

CRediT authorship contribution statement

Eryn D. Gerber: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Camilo Giraldo:** Conceptualization, Data curation, Software, Investigation. **Brett Whorley:** Data curation, Methodology, Writing – review & editing. **Paris Nichols:** Data curation, Investigation, Project administration. **Scott Ring:** Data curation, Investigation, Data curation, Validation. **Carl W. Luchies:** Resources, Writing – review & editing, Supervision.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

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References

Bagherzadeh Cham, M., Mohseni-Bandpei, M. A., Bahramizadeh, M., Forogh, B., Kalbasi, S., & Biglarian, A. (2018). Effects of vibro-medical insoles with and without vibrations on balance control in diabetic patients with mild-to-moderate peripheral neuropathy. *Neurological Sciences, 39*, 1079–1084. https://doi.org/10.1016/j.jbiomech.2020.109656

Bagherzadeh Cham, M., Mohseni-Bandpei, M. A., Bahramizadeh, M., Kalbasi, S., & Biglarian, A. (2016). The clinical and biomechanical effects of subthreshold random noise on the plantar surface of the foot in diabetic patients and elder people: A systematic review. *Prosthetics and Orthotics International, 40*(6), 658–667. https://doi.org/10.1177/0309364616631351

Bergen, G., Stevens, M. R., & Burns, E. R. (2016). Falls and fall injuries among adults aged ≥65 years — United States, 2014. *Morbidity and Mortality Weekly Report, 65*(37), 993–998. https://doi.org/10.15585/mmwr.mm6537a2

Bolbecker, A. R., Apthorp, D., Martin, A. S., Tahayori, B., Moravec, L., Gomez, K. L., … Hetrick, W. P. (2018). Disturbances of postural sway components in cannabis users. *Drug and Alcohol Dependence, 190*(December 2017), 54–61. https://doi.org/10.1016/j.drugalcdep.2018.05.012

Chen, W. M., Li, J. W., Geng, X., Wang, C., Chen, L., & Ma, X. (2020). The potential influence of stochastic resonance vibrations on neuromuscular strategies and center of pressure sway during single-leg stance. *Clinical biomechanics, 77*(May), Article 105069. https://doi.org/10.1016/j.clinbiomech.2020.105069

Costa, M., Priplata, A. A., Lipsitz, L. A., Wu, Z., Huang, N. E., Goldberger, A. L., & Peng, C. K. (2007). Noise and poise: Enhancement of postural complexity in the elderly with stochastic-resonance-based therapy. *EPL (Europhysics Letters), 77*, 1–9.

Degani, A. M., Leonard, C. T., & Danna-dos-Santos, A. (2017). The effects of early stages of aging on postural sway: A multiple domain balance assessment using a force platform. *Journal of Biomechanics, 64*, 8–15. https://doi.org/10.1016/j.jbiomech.2017.08.029

Dettmer, M., Pourmoghaddam, A., Lee, B. C., & Layne, C. S. (2015). Effects of aging and tactile stochastic resonance on postural performance and postural control in a sensory conflict task. *Somatosensory and Motor Research, 32*(2), 128–135. https://doi.org/10.3109/08990220.2015.1004045

Dyck, P. J. (1993). *A 4, 2, and 1 stepping algorithm for quick and accurate estimation of cutaneous sensation threshold*.

Gaerlan, M., Alpert, P. T., Cross, C., Louis, M., & Kowalski, S. (2012). Postural balance in young adults: The role of visual, vestibular and somatosensory systems. *Journal of the American Academy of Nurse Practitioners, 24*(6), 375–381.

Giraldo, C. (2021). *Design, validation and assessment of vibratory mat for stochastic resonance applications*. ProQuest Dissertations and Theses. University of Kansas. Retrieved from https://www.proquest.com/dissertations-theses/design-validation-assessment-vibratory-mat/docview/2560052453/se-2?accountid=8144%0Ahttp://sfx.aub.aau.dk/sfxaub?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:dissertation&genre=dissertations+%26+theses.

Goldberger, A. L., Peng, C. K., & Lipsitz, L. A. (2002). What is physiologic complexity and how does it change with aging and disease? *Neurobiology of Aging, 23*(1), 23–26. https://doi.org/10.1016/S0197-4580(01)00266-4

Hijmans, J. M., Geertzen, J. H. B., Zijlstra, W., Hof, A. L., & Postema, K. (2008). Effects of vibrating insoles on standing balance in diabetic neuropathy. *Journal of Rehabilitation Research and Development, 45*(9), 1441–1450. https://doi.org/10.1682/JRRD.2008.02.0023

Karimi-AhmadAbadi, A., Naghdi, S., Ansari, N. N., Fakhari, Z., & Khalifeloo, M. (2018). A clinical single blind study to investigate the immediate effects of plantar vibration on balance in patients after stroke. *Journal of Bodywork and Movement Therapies, 22*(2), 242–246. https://doi.org/10.1016/j.jbmt.2017.04.013

Kavounoudias, A., Roll, R., & Roll, J. P. (1999). Specific whole-body shifts induced by frequency-modulated vibrations of human plantar soles. *Neuroscience Letters, 266*(3), 181–184. https://doi.org/10.1016/S0304-3940(99)00302-X

Kavounoudias, A., Roll, R., & Roll, J.-P. (1998). The plantar sole is a "dynamometric map" for human balance control. *NeuroReport, 9*(14), 3247–3252. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/9831459%0Ahttps://insights.ovid.com/crossref?an=00001756-199810050-00021.

Lipsitz, L. A. (2002). Dynamics of stability: The physiologic basis of functional health and frailty. *The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences, 57*(3), 115–125. https://doi.org/10.1093/gerona/57.3.B115

Lipsitz, L. A., & Goldberger, A. L. (1992). Loss of "complexity" and aging. *JAMA: The Journal of the American Medical Association, 267*(13), 1806. https://doi.org/10.1001/jama.1992.03480130122036

Lipsitz, L. A., Lough, M., Niemi, J., Travison, T., Howlett, H., & Manor, B. (2015). A shoe insole delivering subsensory vibratory noise improves balance and gait in healthy elderly people. *Archives of Physical Medicine and Rehabilitation, 96*(3), 432–439. https://doi.org/10.1016/j.apmr.2014.10.004

Maki, B. E., & McIlroy, W. E. (1996). Postural control in the older adult. *Clinics in Geriatric Medicine, 12*(4), 635–658.

Manor, B., & Lipsitz, L. A. (2013). Physiologic complexity and aging: Implications for physical function and rehabilitation. *Progress in Neuro-Psychopharmacology and Biological Psychiatry, 45*, 287–293. https://doi.org/10.1016/j.pnpbp.2012.08.020

McDonnell, M. D., & Ward, L. M. (2011). The benefits of noise in neural systems: Bridging theory and experiment. *Nature Reviews Neuroscience, 12*(7), 415–425. https://doi.org/10.1038/nrn3061

McIlroy, W. E., & Maki, B. E. (1997). Preferred placement of the feet during quiet stance: Development of a standardized foot placement for balance testing. *Clinical biomechanics, 12*(1), 66–70. https://doi.org/10.1016/S0268-0033(96)00040-X

Miranda, D. L., Hsu, W. H., Gravelle, D. C., Petersen, K., Ryzman, R., Niemi, J., & Lesniewski-Laas, N. (2016). Sensory enhancing insoles improve athletic performance during a hexagonal agility task. *Journal of Biomechanics, 49*(7), 1058–1063. https://doi.org/10.1016/j.jbiomech.2016.02.022

Nichols, P. (2020). *Quantifying somatosensory deficits using sample entropy and fuzzy sample entropy*. ProQuest Dissertations and Theses. University of Kansas.

Perry, S. D. (2006). Evaluation of age-related plantar-surface insensitivity and onset age of advanced insensitivity in older adults using vibratory and touch sensation tests. *Neuroscience Letters, 392*(1–2), 62–67. https://doi.org/10.1016/j.neulet.2005.08.060

Prieto, T. E., Myklebust, J. B., Hoffmann, R. G., Lovett, E. G., & Myklebust, B. M. (1996). Measures of postural steadiness: Differences between healthy young and elderly adults. *IEEE Transactions on Biomedical Engineering, 43*(9), 956–966. https://doi.org/10.1109/10.532130

Priplata, A. A., Niemi, J., Salen, M., Harry, J., Lipsitz, L. A., & Collins, J. J. (2002). Noise-enhanced human balance control. *Physical Review Letters, 89*(23). https://doi.org/10.1103/PhysRevLett.89.238101

Priplata, A. A., Patritti, B. L., Niemi, J. B., Hughes, R., Gravelle, D. C., Lipsitz, L. A., … Collins, J. J. (2006). Noise-enhanced balance control in patients with diabetes and patients with stroke. *Annals of Neurology, 59*(1), 4–12. https://doi.org/10.1002/ana.20670

Richardson, J. K., & Ashton-Miller, J. A. (1996). Peripheral neuropathy: An often-overlooked cause of falls in the elderly. *Postgraduate Medicine, 99*(6), 161–172.

Roerdink, M., De Haart, M., Daffertshofer, A., Donker, S. F., Geurts, A. C. H., & Beek, P. J. (2006). Dynamical structure of center-of-pressure trajectories in patients recovering from stroke. *Experimental Brain Research, 174*(2), 256–269. https://doi.org/10.1007/s00221-006-0441-7

Roman-Liu, D. (2018). Age-related changes in the range and velocity of postural sway. *Archives of Gerontology and Geriatrics, 77*, 68–80. https://doi.org/10.1016/j.archger.2018.04.007

Shin, S., Motl, R. W., & Sosnoff, J. J. (2011). A test of the rambling and trembling hypothesis: Multiple sclerosis and postural control. *Motor Control, 15*(4), 568–579. https://doi.org/10.1123/mcj.15.4.568

Shin, S., & Sosnoff, J. J. (2017). Spinal cord injury and seated postural control: A test of the rambling and trembling hypothesis. *Motor Control, 21*(4), 443–456. https://doi.org/10.1123/mc.2016-0014

Speers, R. A., Kuo, A. D., & Horak, F. B. (2002). Contributions of altered sensation and feedback responses to changes in coordination of postural control due to aging. *Gait and Posture, 16*(1), 20–30. https://doi.org/10.1016/S0966-6362(02)00003-6

Spielholz, N. I., Dyck, P. J., O'Brien, P. C., Shy, M. E., & Frohman, E. M. (2003). Quantitative sensory testing: Report of the therapeutics and technology assessment Subcommittee of the American Academy of neurology [1] (multiple letters). *Neurology, 61*(11), 1628–1630. https://doi.org/10.1212/WNL.61.11.1628

Stania, M., Sarat-Spek, A., Blacha, T., Kazek, B., Juras, A., Słomka, K. J., … Emich-Widera, E. (2020). Rambling-trembling analysis of postural control in children aged 3-6 years diagnosed with developmental delay during infancy. *Gait and Posture, 82*(September 2019), 273–280. https://doi.org/10.1016/j.gaitpost.2020.09.018

Stephen, D. G., Wilcox, B. J., Niemi, J. B., Franz, J., Casey Kerrigan, D., & D'Andrea, S. E. (2012). Baseline-dependent effect of noise-enhanced insoles on gait variability in healthy elderly walkers. *Gait and Posture, 36*(3), 537–540. https://doi.org/10.1016/j.gaitpost.2012.05.014

Stergiou, N., Harbourne, R. T., & Cavanaugh, J. T. (2006). Optimal movement variability: A new theoretical perspective for neurologic physical therapy. *Journal of Neurologic Physical Therapy, 30*(3), 120–129. https://doi.org/10.1097/01.NPT.0000281949.48193.d9

Strang, A. J., Haworth, J., Hieronymus, M., Walsh, M., & Smart, L. J. (2011). Structural changes in postural sway lend insight into effects of balance training, vision, and support surface on postural control in a healthy population. *European Journal of Applied Physiology, 111*, 1485–1495.

Tahayori, B., Riley, Z. A., Mahmoudian, A., Koceja, D. M., & Hong, S. L. (2012). Rambling and trembling in response to body loading. *Motor Control, 16*(2), 144–157. https://doi.org/10.1123/mcj.16.2.144

Vaillancourt, D. E., & Newell, K. M. (2002). Changing complexity in human behavior and physiology through aging and disease. *Neurobiology of Aging, 23*(1), 1–11. https://doi.org/10.1016/S0197-4580(01)00247-0

Viseux, F., Lemaire, A., Barbier, F., Charpentier, P., Leteneur, S., & Villeneuve, P. (2019). How can the stimulation of plantar cutaneous receptors improve postural control? Review and clinical commentary. *Neurophysiologie Clinique*. https://doi.org/10.1016/j.neucli.2018.12.006

Wang, Y., Watanabe, K., & Chen, L. (2016). Effect of plantar cutaneous inputs on center of pressure during quiet stance in older adults. *Journal of Exercise Science and Fitness, 14*(1), 24–28. https://doi.org/10.1016/j.jesf.2016.02.001

White, O., Johannsen, L., Goswami, N., Trenado, C., & Babič, J. (2019). The promise of stochastic resonance in falls prevention. *Frontiers in Physiology, 9*(January), 1–12. https://doi.org/10.3389/fphys.2018.01865

Whorley, B. (2020). *Physiology-based approach for detecting vibration perception threshold in the plantar foot. ProQuest dissertations and theses*. University of Kansas.

Wickremaratchi, M. M., & Llewelyn, J. G. (2006). Effects of ageing on touch. *Postgraduate Medical Journal, 82*(967), 301–304. https://doi.org/10.1136/pgmj.2005.039651

Winter, D. A., Patla, A. E., & Frank, J. S. (1990). Assessment of balance control in humans. *Medical Progress through Technology, 16*(1–2), 31–51.

Wuehr, M., Boerner, J. C., Pradhan, C., Decker, J., Jahn, K., Brandt, T., & Schniepp, R. (2018). Stochastic resonance in the human vestibular system – Noise-induced facilitation of vestibulospinal reflexes. *Brain Stimulation, 11*(2), 261–263. https://doi.org/10.1016/j.brs.2017.10.016

Zarkou, A., Lee, S. C. K., Prosser, L. A., Hwang, S., & Jeka, J. (2018). Stochastic resonance stimulation improves balance in children with cerebral palsy: A case control study. *Journal of Neuroengineering and Rehabilitation, 15*(1). https://doi.org/10.1186/s12984-018-0467-7

Zatsiorsky, V. M., & Duarte, M. (1999). Instant equilibrium point and its migration in standing tasks: Rambling and trembling components of the stabilogram. *Motor Control, 3*(1), 28–38. https://doi.org/10.1123/mcj.3.1.28

Zhou, J., Lipsitz, L., Habtemariam, D., & Manor, B. (2016). Sub-sensory vibratory noise augments the physiologic complexity of postural control in older adults. *Journal of Neuroengineering and Rehabilitation, 13*(1), 1–8. https://doi.org/10.1186/s12984-016-0152-7

Zwaferink, J. B. J., Hijmans, J. M., Schrijver, C. M., Schrijver, L. K., Postema, K., & van Netten, J. J. (2020). Mechanical noise improves the vibration perception threshold of the foot in people with diabetic neuropathy. *Journal of Diabetes Science and Technology, 14*(1), 16–21. https://doi.org/10.1177/1932296818804552