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Application of vibration to the soles increases long-range correlations in the stride parameters during walking

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ABSTRACT

Temporal fluctuations in the stride parameters during human walking exhibit long-range correlations, but these long-range correlations in the stride parameters decrease due to aging or neuromuscular diseases. These observations suggest that any quantified index of the long-range correlation can be regarded as an indicator of gait functionality. Considering the effect of task-relevant sensory feedback on augmenting human motor performance, we devised shoes with active insoles that could deliver noisy vibration to the soles of feet and assessed their efficacy in enhancing the long-range correlations in the stride parameters for healthy young adults. The vibration could be wirelessly controlled using a smartphone. The actuators, control unit, and battery in the devised shoes were light and embedded in the shoes. By virtue of this compactness, the shoes could be easily used for daily walking outside a laboratory. We performed walking experiments with 20 healthy adults and evaluated the effects of sub- and supra-threshold vibration on long-range correlations in stride interval and length. We performed detrended fluctuation analysis to quantify the long-range correlation of temporal changes in stride interval and length. We found that supra-threshold vibration, applied to the soles with the amplitude of 130 % of the sensory threshold, significantly increased the long-range correlations in stride interval and length by 10.3 % ($p = 0.009$) and 10.1 % ($p = 0.021$), respectively. On the other hand, sub-threshold vibration with the amplitude of 90 % of the sensory threshold had no significant effect. These results demonstrate that additional somatosensory feedback through barely detectable vibrations, which are supplied by compact shoes with active insoles, can enhance the indices of "healthy" complexity of locomotor function.

1. Introduction

Temporal fluctuations in stride parameters during human walking exhibits long-range correlations [1–3]. This finding supports that temporal variation in stride parameters during walking resembles fractal-like structures with complex dynamics and not the stochastic noise [4,5]. Numerous studies have suggested that biological systems with higher complexity are robust against perturbations and have enhanced flexibility [6–9]. This adaptive behavior is inherently essential to maintain functionality. Complex behavior is most prominently observed in rhythmic biological signals originating from the cardiac, respiratory, neural, postural, and

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locomotor systems, which generally break down due to aging and the onset of diseases [10–14]. In particular, previous studies have indicated that aging and neuromuscular diseases decrease long-range correlations in the stride parameters [2,14–16]. These findings suggest that the long-range correlation in the stride parameters can serve as an indicator of gait functionality, and interventions that enhance this indicator can be generally regarded as desirable.

In the field of motor neuroscience, providing task-relevant sensory information is widely accepted as one of the effective interventions to enhance motor performance [17]. For a closed-loop motor task such as walking, numerous sensory organs (visual, vestibular, and somatosensory) provide essential afferent feedback regarding the external environment to make necessary adjustments for maintaining balance [18,19]. Previous studies have shown that modulating vestibular and visual feedback modifies the long-range correlations in the stride parameters during walking [20–22]. However, there is a dearth of studies assessing the role of somatosensory feedback on long-range correlations in the stride parameters. Providing additional afferent feedback to the somatosensory system can be particularly effective for enhancing motor performance as large reciprocal connections exist between motor and somatosensory cortices [23–25]. These connections provide a direct pathway between motor and sensory functions, and additional feedback to the sensory cortex is translated into improving motor performance [26,27]. An abundant source of somatosensation during walking is the foot, which is typically the only point of contact with the ground and contains a large number of mechanoreceptors [19,28,29]. Afferent feedback from these mechanoreceptors is essential to adequately maintain balance during walking by modulating the distribution of stride parameters [30,31].

Applying noisy mechanical vibration to the plantar surface of the feet is an extensively used method to stimulate the mechanoreceptors at the soles. These mechanoreceptors are sensitive to different frequencies [29,32], so applying noisy vibration over a large frequency range can be particularly effective in maximizing the number of stimulated receptors. Active insoles that apply noisy vibration to the soles using small piezoelectric actuators are a non-noxious yet practical method to provide somatosensory feedback. Past studies showed that noisy vibration slightly below or above one's sensory threshold using active insoles improves the balance and gait of healthy young adults and the elderly [33–36]. We recently developed shoes embedded with active insoles that deliver noisy vibration to the soles of feet, which can be wirelessly controlled using a smartphone application [37]. We confirmed the efficacy of these shoes in mitigating declines in the static balance after fatigue, increasing jump height, and improving gait by reducing minimum toe clearance variability [27,37,38].

Two previous studies demonstrate the efficacy of stimulating mechanoreceptors at the soles on long-range correlations in the motor output signals [37,39]. In one previous study, we showed that applying vibration to soles using shoes with active insoles mitigated declines in the long-range correlations in the displacement of the center of pressure while maintaining standing balance [37]. However, the efficacy of that intervention in modulating the long-range correlations in stride parameters was not evaluated. In the other study, which investigated the case of walking, Chien et al. showed that the application of vibration to the soles using active insoles at specific amplitude and frequency increases long-range correlations in the stride interval or length [39]. However, the active insoles used in this study were connected to a control unit fastened around the hip using wires, which could affect the natural motion during walking. In addition, the vibration was applied with a set of specific frequencies and amplitudes, which could hardly stimulate the diverse mechanoreceptors at the soles that are sensitive to a wide range of frequencies. Furthermore, the level of somatosensory feedback perceived by the participants was not the same since the amplitudes of vibration used in the study were not determined with respect to each participant's sensory threshold. Thus, the results of these previous studies cannot clearly conclude whether sub- or supra-sensory threshold stimulus is effective in enhancing long-range correlations in stride parameters.

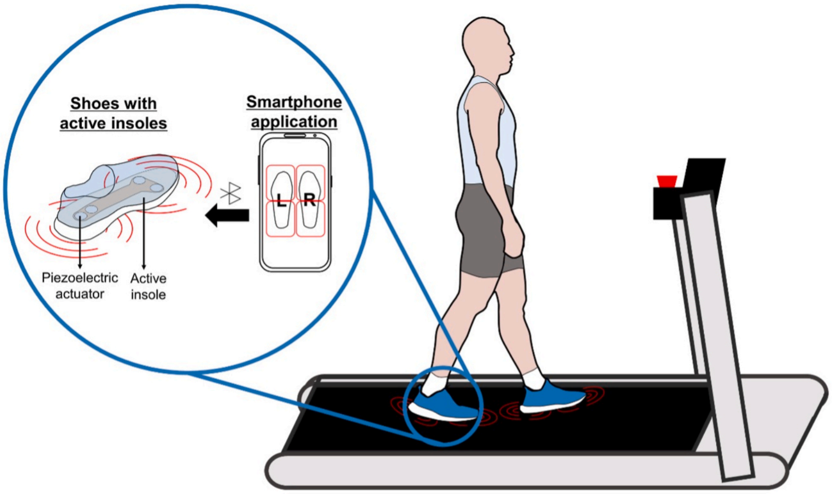

Fig. 1. Illustration of the active insoles and the walking task. The active insoles are embedded with piezoelectric actuators that deliver vibration to the metatarsal head and heel of the both feet. The active insoles are inserted into shoes that contain a rechargeable battery to power the actuators and a charging unit to recharge the battery. The amplitude of vibration is controlled wirelessly via Bluetooth using a customized smartphone application.

Considering these limitations, we aimed to evaluate the effect of sub- and supra-sensory threshold vibrations applied to the soles with a wide range of frequencies on long-range correlations in the stride parameters. We hypothesized that applying vibration to soles increases long-range correlations in the stride interval and length. Using the shoes with active insoles, which delivered vibration through wireless control, we addressed whether this intervention can affect the long-range correlation during walking.

2. Materials and methods

2.1. Participants

Twenty healthy young adults (11 males and 9 females; age: 27.80 ± 4.91 years; height: 169.00 ± 6.60 cm; weight: 65.20 ± 12.62 kg) participated in the study. The participants had no known history of cardiovascular, muscular, orthopedic, or neurological diseases. The institutional review board (IRB) at Seoul National University approved every aspect of the study (IRB No. 2004/001–016), which adhered to the guidelines and principles outlined in the Declaration of Helsinki. We obtained written consent from all the participants before they took part in the study.

2.2. Experimental procedure

The experimental procedure used in this study is described in detail in our previous study [38]. Fig. 1 illustrates the active insoles and the task used in this study. To briefly summarize here, we applied vibration to the soles between the frequencies of 1 and 350 Hz at the metatarsal head and heel using two pairs of piezoelectric actuators embedded into an insole, separately for the left and right foot. The control units of the actuators and rechargeable battery powering it were inserted into the insoles and connected to a charging port constructed into custom-built shoes. The vibration amplitude was controlled independently for each section of the foot wirelessly via Bluetooth using a smartphone application.

First, we estimated the vibration sensory threshold of each participant separately for each foot and section in a sitting position, which is described in detail in our previous studies [27,37,38]. To recap the method, we applied the vibration in an incremental order separately for each section of the foot, and asked the participants to report once they sensed the vibration. We repeated this process three times, and the sensory threshold was determined as the average value. We estimated the threshold for each area of the foot in random order since the metatarsal head and heel have different thresholds for each foot. Then, we measured the preferred walking speed (PWS) of each participant; the PWS estimation process which is explained in our previous studies [38,40] can be outlined as follows. Initially, the participants walked at a speed of 2.5 km/h on a treadmill, and we slowly increased the speed by 0.1 km/h every 10 s. We increased the speed until the participants reported the walking speed to be the best representation of their everyday walking speed. After that, we increased the speed by 1.0 km/h instantaneously, and then decreased the speed by 0.1 km/h every 10 s until the participants reported the walking speed to be the best representation of their everyday walking speed. We repeated this process three times, and the PWS was determined as the average value.

After measuring participants' PWS, we asked them to walk on a treadmill (FDM-TDSL-3i, Zebris Inc®, Germany) at their PWS under three vibration conditions: no vibration (No), sub-threshold vibration (Sub), and supra-threshold vibration (Supra). We attached 20 retroreflective markers to the anatomical landmarks of the lower limb, and recorded the marker positions using ten infra-red cameras (Optitrack Prime^X 13, Natural Point, Inc., Oregon, USA). To calculate the stride parameters, we used the coordinate of markers attached at the heel, and anterior and posterior superior iliac spine.

Participants completed three trials of walking under the three vibration conditions in a randomized order. Consulting a previous study [41], we instructed the participants to walk 10 min for the first trial and 7 min each for the next two trials with 5 min of rest between trials; we used the data only during the last 5 min of the walking trials as the initial 5 min in the first trial and 2 min in the subsequent trials were considered as the time required for treadmill acclimatization. For the Sub and Supra conditions, the vibration was turned on during the last 5 min of the walking trials. We selected 90 % and 130 % of the sensory threshold as the amplitudes of vibration for the Sub and Supra conditions, respectively; these amplitudes of vibrations were most beneficial for motor performance enhancement during postural control, jump, and walking tasks [27,35,38,42].

2.3. Data processing

We filtered the raw coordinates of the reflective markers using a zero-lag low-pass Butterworth filter with a cut-off frequency of 10 Hz. We then calculated the stride interval as the time between two consecutive dominant foot heel strikes, and we calculated the stride length as the distance traveled by the marker attached to the heel between two consecutive dominant foot heel strikes. Using the method proposed in Zeni et al. [43], we selected the moment of heel strike as the time point of the local maximum of the anterior-posterior distance between the heel marker and the center of mass of the pelvis. The time series of the stride parameters during the 5-min data acquisition period under each condition were obtained. To quantify the long-range correlation of temporal changes in stride parameters, we performed a detrended fluctuation analysis using the time series during the 5-min period and extracted the scaling exponent, α, following the method introduced by Peng et al. [44].

First, we defined the stride parameters (stride interval or length) as X. Next, we generated the integrated time series of X, X_{int} by cumulatively summing X over the total number of strides, N for 5 min of treadmill walking as in equation (1);

$$X_{int}(k) = \sum_{i=1}^{k}\left(X(i) - X_{avg}\right), \tag{1}$$

where $X(i)$ and X_{avg} are the ith stride parameter and average stride parameter, and $k = 1, 2, ..., N$. Next, we divided $X_{int}(k)$ into non-overlapping windows of length n. For each window length n, we calculated a local least fit line to define the fitted value as $X_{det}(k)$. We increased the window size with increments of evenly divided 50 values between the initial value of 4 and the final value of $N/4$ based on the criteria proposed in previous studies [45,46]. Then, we calculated the root mean square fluctuations of $X_{int}(k)$ with respect to the locally fitted line for each window size n as in equation (2);

$$F(n) = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left[X_{int}(k) - X_{det}(k)\right]^2}. \tag{2}$$

Here, $F(n)$ is the detrended fluctuation parameter that obeys a power-law function; $F(n) \propto n^{\alpha}$. The value of α is obtained as the slope of the linear regression of log $F(n)$ over log n. Long-range correlations exist for temporal changes in stride parameters when the values of α are between 0.5 and 1; it is maximally complex when $\alpha = 1$.

2.4. Statistical analysis

To evaluate significant differences in the values of average, standard deviation, and α of stride interval and length for 20 participants depending on the vibration conditions (No, Sub, and Supra), we used one-way repeated measures analysis of variance (ANOVA). If significant main effect of vibration conditions were identified, we used Bonferroni correction as a post-hoc test for multiple pairwise comparisons between conditions. We reduced the degrees of freedom using the Greenhouse-Geisser criterion, if the assumption of

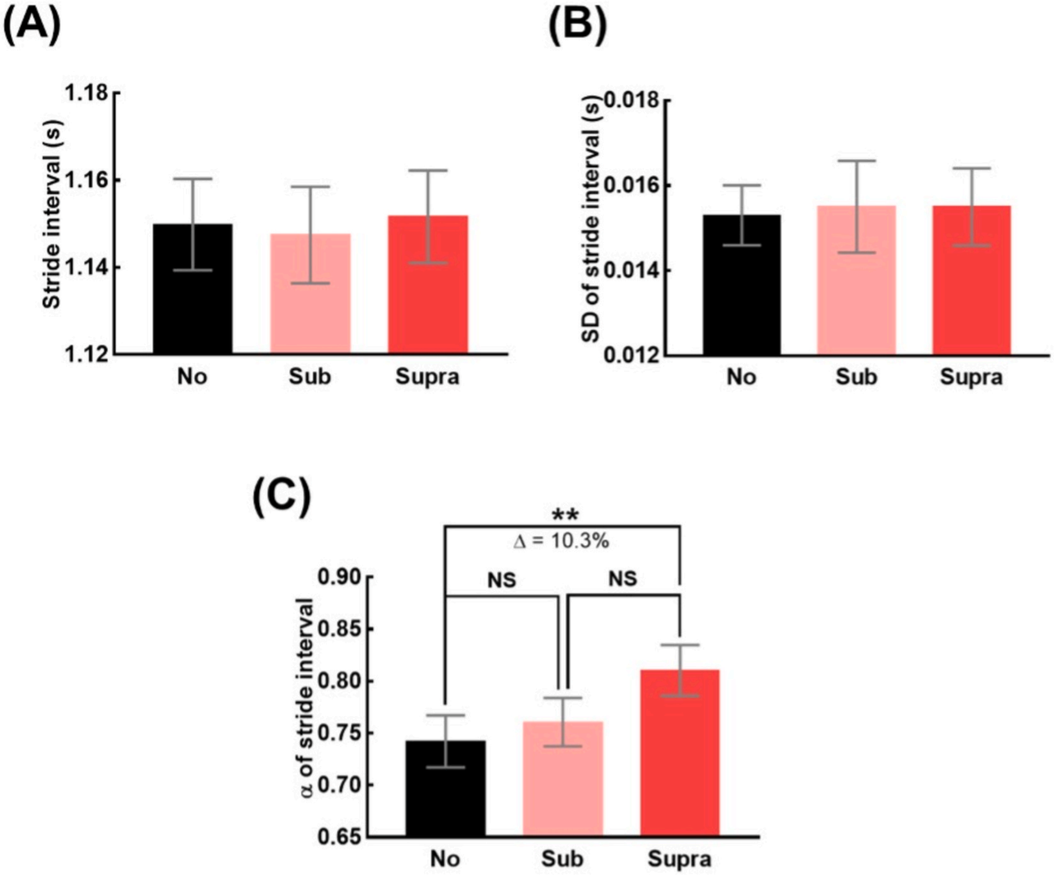

Fig. 2. Changes in the distribution and long-range correlations in stride intervals due to vibrations. (A–C) show the mean and standard error bars of the average, standard deviation, and α exponent values of stride intervals for 20 participants, respectively, under the three vibration conditions: no vibration (No), sub-threshold vibration (Sub), and supra-threshold vibration (Supra). Statistically significant difference is indicated using double asterisk (**: $p < 0.01$), whereas no statistically significant difference is indicated using NS. We quantified the increase in α exponent values with statistical significance as Δ (%), which is the percentage difference with respect to the smaller values.

sphericity, evaluated using Mauchly's test, was violated. We set the level of statistical significance at $p < 0.05$.

3. Results

Fig. 2 (A-C) and Fig. 3 (A-C) show the mean and standard error of the average, standard deviation, and α values of stride interval and length for 20 participants. No significant main effect of vibration conditions was revealed on the average and standard deviation values for both stride interval (average: F [2,38] = 1.053, p = 0.359; standard deviation: F [2,38] = 0.031, p = 0.970) and length (average: F [1.523, 29.099] = 0.667, p = 0.482; standard deviation: F [2,38] = 0.247, p = 0.782). On the other hand, significant main effects of vibration conditions were revealed for α values for both stride interval (F [2,38] = 7.287, p = 0.002) and length (F [2,38] = 4.163, p = 0.023). Pairwise comparisons revealed that the α values for both stride interval and length under Supra condition were significantly higher than the values under No condition (stride interval: p = 0.009; stride length: p = 0.021). However, no significant differences were observed between the No and Sub conditions (stride interval: p = 0.612; stride length: p = 1.000), and between the Sub and Supra conditions (stride interval: p = 0.076; stride length: p = 0.206). The percentage increase in the α values under Supra condition with respect to the values under No condition is designated as Δ (%) in Fig. 2 and Fig. 3. The mean Δ values were greater than 10 % with respect to No condition.

4. Discussion

Complexity observed in signals from the cardiac, respiratory, neural, postural, and locomotor systems generally diminishes owing to aging or diseases [10–14]. Specifically, considering the clear correlation between the decrease in long-range correlations in the stride parameters and gait deficits caused by aging and neuromuscular diseases [2,14–16], the long-range correlation in the stride parameters can be regarded as an indicator of locomotor functionality. In this study, we demonstrated the efficacy of noisy vibration to

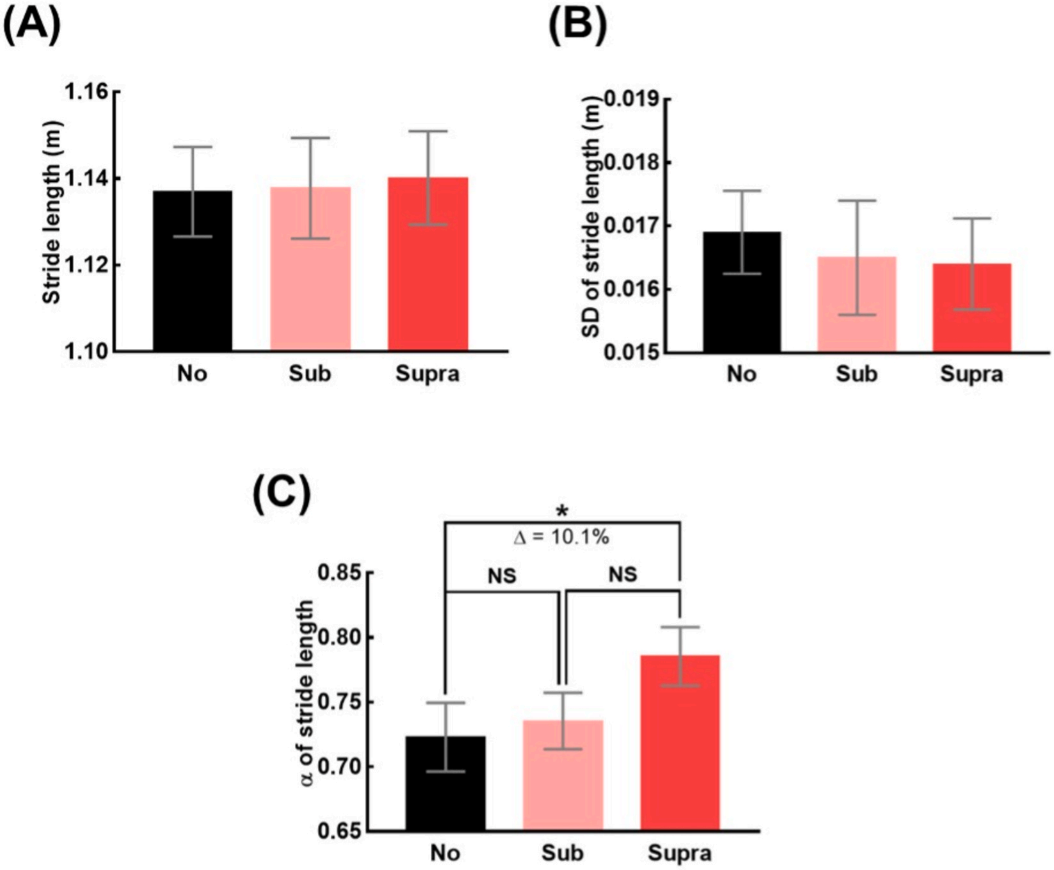

Fig. 3. Changes in the distribution and long-range correlations in stride lengths due to vibrations. (A–C) show the mean and standard error bars of the average, standard deviation, and α exponent values of stride lengths for 20 participants, respectively, under the three vibration conditions: no vibration (No), sub-threshold vibration (Sub), and supra-threshold vibration (Supra). Statistically significant difference is indicated using single asterisk (*: $p < 0.05$), whereas no statistically significant difference is indicated using NS. We quantified the increase in α exponent values with statistical significance as Δ (%), which is the percentage difference with respect to the smaller values.

the soles in increasing the complexity of the time series of the stride parameters particularly for healthy young adults. Supra-threshold vibration significantly increased the long-range correlations in the stride interval and length without noticeable differences in their average and standard deviation.

Multiple factors might contribute to the observed increase in the long-range correlations. First, the detectable vibration with the amplitude beyond sensory threshold might affect sensorimotor integration. Additional afferent feedback to the somatosensory system via the application of vibration to the soles increases the sensitivity to detect weak mechanical signals [47,48]. The enhanced sensitivity augments sensorimotor integration, possibly increasing the long-range correlations in the motor outputs. Another plausible explanation for the increased complexity is the modulation of the rhythmicity of the movement due to external stimulus. Previous studies have suggested that altering the afferent feedback to the auditory and visual systems modulates sensorimotor synchronization to augment long-range correlations [20–22].

It is noteworthy that the supra-threshold vibration affected the long-range correlations of the stride parameters without altering their average and standard deviation. This result suggests that the barely detectable stimulus changed the motor output only to the extent that the effects might not be revealed by simply comparing conventional statistical summaries like average and standard deviation [2,7,49–51]. Multiple previous studies support that a time-series analysis of the dynamics of the motor output signals is necessary to characterize subtle changes in human motor behaviors. According to the study by Lipsitz and Goldberger, the elderly and young have similar average and standard deviation of the heart rate, but the structure of the time series of heart rates is vastly different, resulting in a significant decline in long-range correlations for the elderly [7]. In another study, Hausdorff et al. reported a significant decrease in the long-range correlations in stride intervals due to aging, whereas the average and standard deviation remained unchanged [2]. Herman et al. reported no difference between the stride interval variabilities of elderly fallers and those of non-fallers, but they found a significant difference in long-range correlations between the two groups [51]. All these indicate that the long-range correlation serves as a more sensitive index of functionality and frailty.

Chien et al. reported that manipulating the amplitude of vibration increased the long-range correlation of stride interval, whereas manipulating its frequency increased the long-range correlations of stride length [39]. The authors claimed that tactile stimuli can affect long-range correlations of stride interval and length differently, and highlighted the importance of independent control of step interval and length by manipulating vibration properties. They tried to relate these findings with other studies that reported separate control of spatial and temporal aspects of gait by cerebellar and cortical structures [52,53], expanding its implications for treating gait disorders that affect a single aspect of stride parameters.

In contrast, our intervention increased the long-range correlation of both stride interval and length. This distinction between our results and the results in the previous study by Chien et al. [39] might result from the different intervention methods. First, we minimized any mechanical interference other than the vibration by applying the vibration through wirelessly controlled insoles entirely embedded in shoes. By contrast, Chien et al. applied vibration using insoles connected to a control unit fastened around the hip through wires. Second, we determined the amplitude of the vibration based on the sensory threshold of each participant to ensure that the level of somatosensory feedback perceived by each participant remained the same, whereas Chien et al. applied vibration at three fixed amplitudes. Third, we applied vibration over a wide range of frequencies to stimulate various frequency-sensitive mechanoreceptors [29,32] at the soles across participants, whereas Chien et al. applied vibration at three fixed frequencies. Our result, the simultaneous increase in the complexity of both stride parameters might be attributed to the larger amount of mechanoreceptors evoked by the vibration with much wider range frequencies.

We found that supra-threshold vibration (130 % of the sensory threshold) effectively increased the long-range correlations of spatial and temporal stride parameters, whereas sub-threshold vibration (90 % of the sensory threshold) had minimal effect on healthy young adults. In previous studies, our research group and others have also shown that the application of vibration at 130 % of the sensory threshold improved balance for mildly challenging postural control task, increased jump height, and reduced the minimum toe clearance variability and the risk of tripping for healthy young adults [27,38,42]. These results suggest that applying vibration with the amplitude of 130 % of the sensory threshold may be a viable method for improving the performance of healthy young adults in various motor tasks.

In contrast, past studies have shown that even sub-threshold vibration to the soles affect the variability of stride parameters for the healthy and fall-prone-elderly [34,54]. In addition, sub-sensory threshold vibration to the soles was reported to improve motor performance of individuals with peripheral neuropathy [55]. The degradation of somatosensation due to aging or disease is the possible explanation for this benefit of even weaker noisy vibration to the soles. Previous studies have reported that the optimum level of noise that maximally enhances human motor performance differs with age and onset of diseases [48,56,57]. Hence, future studies assessing the feasibility of noisy vibration to the soles on the long-range correlations of stride parameters for the elderly, and individuals with neuromuscular diseases or peripheral neuropathy-induced somatosensory impairments may need to consider both sub- and supra-threshold vibrations.

In this initial study, we selected only two amplitudes of vibration (90 % and 130 % of the sensory threshold) to minimize the length of experimental protocol and any possible artifact due to fatigue. Although we selected these specific amplitudes consulting the previous studies that reported their efficacy in improving motor performance in various tasks [27,35,38,42], we cannot guarantee that these values are optimal for increasing long-range correlations in the stride parameters. Future studies for finding the optimal amplitude of vibration that maximally increases long-range correlations in the stride parameters may be considered to further improve the efficacy of the devised intervention. In addition, our study demonstrated only the short-term effects of the proposed intervention on long-range correlations in the stride parameters, but long-term exposure to vibration may cause discomfort or fatigue and diminish human motor performance [58,59]. Therefore, it is necessary to investigate the long-term effects of the proposed intervention and assess any potential side effects of prolonged exposure to the noisy vibration in a future study.

Despite the aforementioned limitations, it is worth clarifying the practicality of the devised technology. First, the shoes we used to deliver the effective intervention do not substantially differ from typical athletic shoes in terms of weight and compactness; the actuators used to deliver the vibration are light, and the battery and control units are compactly embedded into the shoes. Second, the amplitude of vibration is easily controlled using a smartphone application without any wire. These unique features of our intervention method enable the vibration to be applied during daily walking, even outside the laboratory environment. Considering that an increase in long-range correlations in the motor signals indicates higher "healthy" complexity or flexibility, this study presents the potential of a practical method for enhancing the complexity of the stride parameters and augmenting locomotor function.

Ethics statement

The institutional review board (IRB) at Seoul National University approved every aspect of the study (IRB No. 2004/001–016), which adhered to the guidelines and principles outlined in the Declaration of Helsinki. We obtained written consent from all the participants before they took part in the study.

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Data availability statement

All data sets collected and/or analyzed during the current study are available from the corresponding author (Jooeun Ahn) on reasonable request.

Additional information

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CRediT authorship contribution statement

Prabhat Pathak: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft. **Jooeun Ahn:** Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Jooeun Ahn reports financial support was provided by Korea Ministry of Health and Welfare. Jooeun Ahn reports financial support was provided by Korea Ministry of Trade Industry and Energy. Jooeun Ahn reports financial support was provided by National Research Foundation of Korea. Jooeun Ahn has patent #US 11647806 B2 issued to SNU R&DB Foundation and Samsung Electronics. Jooeun Ahn has patent #EP3797626 issued to SNU R&DB Foundation and Samsung Electronics. Prabhat Pathak has patent #US 11647806 B2 issued to SNU R&DB Foundation and Samsung Electronics. Prabhat Pathak has patent #EP3797626 issued to SNU R&DB Foundation and Samsung Electronics. The active insole shoes used in this study were developed by Samsung Electronics, and these shoes might be commercialized in the future. However, Samsung Electronics had no role in the study design, in the collection, analysis and interpretation of data; in the writing of the manuscript; and in the decision to submit the manuscript for publication. These facts do not alter our adherence to Heliyon policies on sharing data and materials.

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