# Effects of subthreshold electrical stimulation with white noise, pink noise, and chaotic signals on postural control during quiet standing

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(Citation)
Gait & Posture, 94:39-44

(Issue Date)
2022-05

(Resource Type)
journal article

(Version)
Accepted Manuscript

**Highlight**

・Somatosensory system can be enhanced via stochastic resonance.

・We explored how stimulation with different signal structures affect postural control.

・Pink noise was effective in reducing postural sway via the stochastic resonance.

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## Abstract

### Background

The stochastic resonance (SR) phenomenon has been used to improve postural control through the application of imperceptible noise to the somatosensory system. White noise signals have been applied in numerous SR studies on postural control. However, because the SR effect depends on the noise structure, the stimulation effects of signals with different structures, such as pink noise and chaotic signals, on postural control, must be determined to achieve better clinical applications of SR technology.

### Research question

During quiet standing, how is postural control affected by subthreshold electrical stimulation to the knee joints when signals with different structures (white noise, pink noise, and chaotic signals) are used?

### Methods

Sixteen healthy young adults stood quietly for 40 s with their eyes closed. To evaluate postural sway, we calculated the mean velocity, root mean square ($CoP_{RMS}$), and range ($CoP_{Range}$) values for the center of pressure (CoP) in the anteroposterior direction. The standing task was conducted under subthreshold electrical stimulation with white noise, pink noise, and chaotic signals based on the Lorenz system, in addition to the no-stimulation condition. The four stimulation conditions were randomized within each set and repeated seven times.

**Results**

Significant stimulation effects were observed in the $CoP_{RMS}$ and $CoP_{Range}$ values. The $CoP_{RMS}$ value under the pink noise signal was significantly lower than that under the no-stimulation condition. The $CoP_{Range}$ value also tended to decrease under the pink noise signal compared with the no-stimulation condition; however, the differences were not statistically significant. No significant changes were found with the white noise and chaotic signals compared with the no-stimulation condition.

**Significance**

We demonstrated that the pink noise signal was more effective in reducing postural sway than the white noise and chaotic signals based on the Lorenz system during quiet standing.

**Keywords:** Stochastic resonance, pink noise, somatosensory system, quiet standing

## 1. Introduction

Postural control is necessary for most activities of daily living; inadequate postural control may lead to detrimental incidents such as falls [1]. Processing and integrating sensory inputs from the somatosensory, visual, and vestibular systems are required for postural control, and the decline in the functions of such sensory systems is associated with postural instability [2,3]. In particular, individuals with proprioception deterioration at the knee joint may display large postural sway during standing [4]. Thus, intervention to enhance their sensory input at the knee joint and ensure postural control [5,6] could significantly improve their quality of life.

The stochastic resonance (SR) phenomenon has been observed in several physiological systems, including the somatosensory system [5–9]. As an application of the SR theory, the detection and transmission of a weak input signal by somatosensory receptors can be enhanced by imperceptible noise with optimal intensity, leading to postural control via improved body sway feedback [10]. Reductions in postural sway using the SR effect have been observed in several populations [6,11]. A previous study demonstrated that the application of electrical stimulation to the knee joint reduced postural sway during one-legged stance in older adults [6]. Another study also reported such an effect on postural sway when vibrating insoles were applied during two-legged stance in patients with diabetes and stroke [11]. Therefore, improving the SR effect may be a good approach to attain additional gains in postural control.

Numerous SR application studies have used mechanical or electrical stimulation with white noise [5,6,8], whereas some modeling studies observed SR-like phenomena in a bistable system using external chaotic signals [12,13]. A chaotic signal is defined as a signal that is aperiodic, bounded, deterministic, and sensitive to initial conditions [14]. Moreover, it can have a unique Fourier amplitude spectrum [15]. These previous studies suggest that a chaotic signal may produce an effect on postural control that is similar to that of a white noise signal.

In contrast, the significant contribution of pink noise to the SR effect has been shown in several studies. A recent study that used an artificial neuron model as an SR system that received the noise revealed that stimulation with pink noise enhanced the SR effect more than stimulation with noise of other colors, including white noise [16]. The functional advantage of pink noise in the SR phenomenon has also been shown in human studies [7,17], and it has been revealed that the application of weak pink noise to the brainstem via vestibular afferents was more effective in invoking SR in the brain stem baroreflex centers than the application of weak white noise [17]. Moreover, the application of subthreshold vibration with pink and white noise signals to patients with unilateral transtibial amputation revealed that vibration with pink noise was more effective in reducing postural sway during quiet standing than that with white noise [7]. However, such mechanical stimulation may have limitations in the practical application of SR. This is because it may be difficult to maintain the intensity of mechanical noise at the optimal level for SR as a result of undesirable fluctuations in the contact pressure between the skin and vibration actuator. These fluctuations may be caused by several phenomena during daily activities, including skin stretching during joint movement, inertial force during body movement, and changes in the direction of the contact area from the vertical direction.

Moreover, a previous study observed significant increases in sensory thresholds due to vibration stimulation [18]. Therefore, electrical noise stimulation with pink noise may be more beneficial in the practical application of the SR effect in daily activities; however, no studies have investigated the effects of subthreshold electrical stimulations with different signal structures on postural control.

Therefore, this study aimed to explore how applications of subthreshold, imperceptible electrical stimulations with different signal structures (white noise, pink noise, and chaotic signals) to the somatosensory system affect postural control. We hypothesized that the improvement in postural control due to stimulation with pink noise would be greater than that with white noise, and that the improvements with the chaotic signal and white noise would be similar.

## 2. Methods

### *2.1 Participants*

Sixteen young adults (age, 22 ± 1 years; height, 154.4 ± 0.9 cm; mass, 59.6 ± 8.6 kg; mean ± standard deviation), eight male and eight female, with no neurological, muscular, and/or orthopedic conditions, participated in this study. All the participants were right-leg dominant. Before the experiments, all the participants provided written informed consent, and the study was approved by the Human Ethics Committee of the Graduate School of Human Development and Environment at Kobe University. This study was performed in accordance with the principles of the Declaration of Helsinki.

*2.2 Noise and chaotic signal generation*

A customized MATLAB R2019a program (Mathworks, Natick, MA) was used to generate white noise, pink noise, and chaotic signals. Generally, the power spectral density, as a function of the frequency (*f*), is constant and proportional to 1/*f* for white and pink noise. In this study, a discrete time series for the white noise signal, with a sampling frequency of 10 kHz, was first created using the MATLAB function randn (). Next, we applied the MATLAB function fft () to the white noise signal to compute the Fourier transform. Subsequently, the Fourier transform was multiplied by $1/\sqrt{f}$, where $f$ represents the frequency (Hz). Finally, it was converted to a pink noise signal by the inverse Fourier transform using the MATLAB function ifft (). In addition, a chaotic signal was generated by the numerical simulation of the Lorenz attractor, based on a previous study [15]. The equations are as follows:

$$\begin{cases} \dfrac{dx}{dt} = \sigma(y - x) \\ \dfrac{dy}{dt} = x(\rho - z) - y, \\ \dfrac{dz}{dt} = xy - \beta z \end{cases}$$

where $\sigma = 10$, $\rho = 28$, and $\beta = 8/3$ [15]. A series of $x$ projections in the Lorenz attractor was used as the chaotic signal and converted to a 10 kHz discrete time series. An example of a time series generated by the MATLAB program and its recalculated power spectral density is shown in **Figure 1A**. Stimulation with the raw pink noise or chaotic signal may cause continuous polarization at high intensity, resulting in an undesirable temperature rise or pain on the skin below the electrodes [19,20]. Therefore, the raw noise and chaotic signals were modulated by continuous square waves using an electrical stimulator (duty cycle 50%, pulse duration 0.15 ms) (**Figure 1B**). Examples of the power spectral densities of the modulated white noise, pink noise, and chaotic signals are presented in **Figure 1B**. To ensure that the intended stimulation signals were generated, we calculated the slopes of the power spectral densities for the original white noise, pink noise, and chaotic signals, prior to the experiment.

### *2.3 Electrical stimulation*

Two pairs of stimulation electrodes (Ag/AgCl, 18 × 36 mm; F-150-S, Nihon-Kohden, Tokyo, Japan) were placed on the lateral and medial joint spaces of both knees of the participants; the electrical stimulation was generated by two stimulators (SEN-3401, Nihon-Kohden and 3F46, Sanei, Tokyo, Japan). The knee joints were selected as the stimulation points in this study because their proprioception deterioration affects postural control during standing [4]. As shown in **Figure 2**, the original noise or chaotic signal generated by the MATLAB code was output to the electrical stimulators through a data acquisition (DAQ) device (USB-6212, National Instruments, Austin, TX) at 10 kHz, and controlled by a customized LabVIEW program (National Instruments). The modulated stimulation signals (which were the same for both knees) were simultaneously obtained as output from the two stimulators to both knees through the isolator devices (**Figure 2**).

### *2.4 Experimental procedure*

The participants stood quietly on a force platform (N5901, Sanei, Japan) for 40 s with their eyes closed and their arms at the sides of their body. While standing, their feet were parallel at hip width, and their foot positions were marked on the platform to ensure that consistent positions were used across the trials. The participants were instructed to relax and allow natural body sway. They were also asked not to keep their body rigidly aligned and not to intentionally oscillate their body while standing. The standing task was conducted under the following four stimulation conditions: no stimulation, and stimulations using the white noise, pink noise, and chaotic signals. Each electrical stimulation was continuously provided throughout the 40 s standing task.

Before the standing task, the sensory threshold (mA) of each knee was determined for each of the electrical stimulations while in a sitting position with the knee extended, using the white noise, pink noise, and chaotic signals. The order of the stimulation types was randomized among the participants. To determine each threshold, the intensity of the electrical stimulation was gradually increased until the participant detected the signal, and then slowly decreased until the participant was unable to detect it [21]. The threshold was defined as the highest intensity that a participant could not sense, and a stimulation intensity equal to 50% of the threshold was applied during the standing task [21]. Following practice trials, to confirm that no participants felt the stimulation during quiet standing, the four stimulation conditions were randomized within each set. Each set was repeated seven times (28 trials in total), and the stimulation conditions were re-randomized in each set. Approximately 1 min rest periods during standing were provided between trials, and rest periods of a minimum length of 5 min while seated in a chair were provided between sets. After each set, all the participants were asked if they had detected the electrical stimulation while standing.

### *2.5 Data processing*

The force plate signals (i.e., the vertical forces at the four corners of the force plate) were sampled at 100 Hz (PowerLab 16/30, AD Instruments, Sydney, Australia). These signals were low-pass filtered at 15 Hz using a fourth-order zero-lag Butterworth filter [22]. The foot center of pressure in the anteroposterior direction ($CoP_{AP}$) was calculated using the force plate signals. We focused on the $CoP_{AP}$ during quiet standing in this study, because it is associated with the ability to achieve postural control [23,24]. The data for the first and last 5 s of each trial were removed, and data from the middle 30 s were used for further analysis [25,26].

Based on previous studies [24,27], the following center of pressure (CoP) measures were calculated as indices for evaluating postural control: the mean velocity of the center of pressure ($CoP_{MV}$), root mean square of the mean $CoP_{AP}$ ($CoP_{RMS}$), and range of the $CoP_{AP}$ values ($CoP_{Range}$). $CoP_{MV}$ was calculated as the total path length of the $CoP_{AP}$ divided by time. $CoP_{RMS}$ and $CoP_{Range}$ (the difference between the maximum and minimum $CoP_{AP}$ values) were based on the $CoP_{AP}$ position time series. All the measures were normalized using the foot length (%) because of the large variations in the base of support among the participants (foot length: 22.0–27.0 cm) [27], and the averages of the seven trials under each condition for each participant were used for the statistical analysis.

*2.6 Statistical analysis*

The data are presented as the mean ± standard error values. All the statistical tests were performed using SPSS version 26 (IBM, Armonk, NY, USA). Because deviations from a normal distribution were observed with Kolmogorov–Smirnov tests, non-parametric alternatives were used for all the measures.

To test whether the subthreshold electrical stimulation affected the CoP measures during quiet standing, Friedman tests were performed. To determine the differences between the stimulation conditions (the white noise, pink noise, and chaotic signal conditions) and the no-stimulation condition, Wilcoxon signed-rank tests were performed for each measure. We also conducted Friedman tests to determine whether there were any differences in the sensory threshold and range (i.e., largest minus smallest) values of the pulse amplitudes among the signals. The significance level was set at $p = 0.05$ for the Friedman test, and $p$-values adjusted using the Holm correction were applied in the Wilcoxon signed-rank tests [28]. When there was a significant difference, the effect size ($r$) was evaluated according to Cohen's classification [29], and the percentage of reduction was calculated.

## 3. Results

The sensory thresholds were 0.30 ± 0.07 mA, 0.32 ± 0.10 mA, and 0.27 ± 0.07 mA for the white noise, pink noise, and chaotic signals, respectively. The ranges of pulse signal amplitudes were 0.13 ± 0.03 mA, 0.15 ± 0.05 mA, and 0.11 ± 0.03 mA for the white noise, pink noise, and chaotic signals, respectively. There were no significant differences in the sensory threshold ($\chi_r^2$ (2) = 0.87, $p$ = 0.647) and range values of the pulse amplitudes ($\chi_r^2$ (2) = 4.59, $p$ = 0.101) among the signals, and the participants reported that they were not aware of the presence of stimulation during the standing trials.

**Table 1** lists the data for the $CoP_{AP}$-related measures under each condition. The stimulation had significant effects on $CoP_{RMS}$ and $CoP_{Range}$ ($CoP_{RMS}$, $\chi_r^2$ (3) = 15.95, $p$ = 0.001; $CoP_{Range}$, $\chi_r^2$ (3) = 11.75, $p$ = 0.008); however, no significant effect on $CoP_{MV}$ ($\chi_r^2$ (3) = 1.27, $p$ = 0.736) was observed. The value of $CoP_{RMS}$ under the pink noise signal condition was significantly lower than that under the no-stimulation condition (95% confidence interval, 0.08–0.39, $p$ = 0.010), and the effect size was large ($r$ = 0.61). The median value for the amount of $CoP_{RMS}$ reduction under the pink noise signal condition was 9.91% compared to the no-stimulation condition. The value of $CoP_{Range}$ also decreased under the pink noise signal condition; however, the difference was not statistically significant. For all the measures, no significant differences were found under the white noise signal and chaotic signal conditions compared with the no-stimulation condition.

## 4. Discussion

The purpose of this pilot study was to determine the effects of subthreshold white noise, pink noise, and chaotic signals on postural sway during quiet standing with the eyes closed. Compared with the no-stimulation condition, a significantly lower $CoP_{RMS}$ and tendency toward a lower $CoP_{Range}$ were observed under the stimulation of the pink noise signal, whereas no significant changes were found under the stimulation of the white noise and chaotic signals. Our findings supported our hypothesis that the reductions in postural sway due to stimulation with a pink noise signal would be greater than those due to stimulation with white noise and chaotic signals.

Pink noise was observed to have an effect on $CoP_{RMS}$ and potentially on $CoP_{Range}$ (although the change in $CoP_{Range}$ did not reach the level of statistical significance). This difference was not observed in the $CoP_{MV}$ values. $CoP_{MV}$ has different characteristics from $CoP_{RMS}$ and $CoP_{Range}$; $CoP_{RMS}$ and $CoP_{Range}$ are associated with the effectiveness of the postural control system, whereas $CoP_{MV}$ reflects the amount of regulatory balancing activity related to the stability level [24]. Based on the drift and act hypothesis, $CoP_{RMS}$ and $CoP_{Range}$ become larger when the CoP substantially deviates from the equilibrium point before the postural control system detects this CoP deviation and adjusts the posture [3,30,31]. Because somatosensory deficits can cause a degeneration in the ability to detect CoP deviation [32], enhancing the somatosensory system using pink noise might facilitate the detection of CoP deviation, resulting in a decreased $CoP_{RMS}$. Considering the fact that the value of $CoP_{Range}$ is less affected by differences in the standing conditions and populations than the value of $CoP_{RMS}$ [33,34], the value of $CoP_{Range}$ might reach statistical significance during more challenging standing conditions that require a larger ankle torque [35]. Therefore, subthreshold stimulation with pink noise is a potential tool for balance rehabilitation, particularly for patients with a large CoP deviation that could be improved. However, the mechanism of the pink noise effect remains unclear.

In contrast to our results, previous studies revealed that electrical stimulation of the knee joint using a white noise signal improved postural control [5,6]. This contradiction could be a result of signal configuration differences. The previous studies administered continuous white noise signals [6] or constant intensity of successive pulses where the interpulse intervals were randomly assigned [5], whereas in this study, we used combined signals consisting of continuous waves (white noise, pink noise, and chaotic signals) and square waves (**Figure 2**). Continuous waves, and particularly those with long-range correlations such as pink noise, can increase the risk of an undesirable temperature rise as a result of the persistent polarization of the skin [19,20]. Thus, successive pulse signals with pink noise-like interpulse intervals may be more effective for SR applications than the combined signals used in this study. Another reason for the contradiction may be differences in the manner in which the postural tasks were conducted. A previous study [6] had participants stand with their eyes open, whereas, in this study, they stood with their eyes closed. Sensory reweighting with closed eyes [3] may have affected our results. Hence, future studies are warranted to compare the effects of the applied signal on various standing tasks.

The clinical significance of this study is that it supports the use of pink noise to reduce sway amplitude. In this study, the pink noise stimulation condition reduced the $CoP_{RMS}$ value by a median of 9.91% compared to the no-stimulation condition. The amount of reduction observed in this study is clinically relevant, given that a previous study reported an average increase in $CoP_{RMS}$ of 10.7% by aging [27]. The present results highlighted the advantages of using pink noise in the potential application of SR to postural control. Future studies will be needed to verify the effects of electrical stimulation using pink noise on different populations and in other tasks (e.g., walking or standing under more challenging conditions). This will make it possible to maximize the clinical benefits of such stimulation. The risks of electrical stimulation, including pain [20] and muscle damage [36], should also be considered.

This study had some limitations. First, we did not standardize the ranges for the different signals. However, we found no significant differences among the signals, which made us confident that the observed differences were due to the signal structure differences rather than differences in the magnitude of variability. Second, we used combined signals instead of the actual signals to avoid undesirable effects. Third, because this pilot study required repeated standing trials to determine the most effective noise structure, we adopted younger adults as a fundamental study population. Thus, it remains unclear whether similar results will be obtained in individuals with impaired balance. Fourth, the rest period between trials might have been insufficient. Therefore, there might have been carryover effects from the previous condition. Fifth, large electrical stimulators were used in this study; a portable device for electrical stimulation is needed for the clinical application of SR. Future studies are needed to overcome these limitations.

## 5. Conclusions

Our findings supported the hypothesis that a pink noise signal is effective in reducing postural sway during standing, and can provide useful information for the application of the SR effect.

## Conflicts of interest

None.

## References


[1] L.Z. Rubenstein, A.S. Robbins, K.R. Josephson, B.L. Schulman, D. Osterweil, The value of assessing falls in an elderly population. A randomized clinical trial, Ann. Intern. Med. 113 (1990) 308–316. https://doi.org/10.7326/0003-4819-113-4-308.

[2] R.J. Peterka, Sensory integration for human balance control, Handb. Clin. Neurol. 159 (2018) 27–42. https://doi.org/10.1016/B978-0-444-63916-5.00002-1.

[3] R.J. Peterka, Sensorimotor integration in human postural control., J. Neurophysiol. 88 (2002) 1097–1118. https://doi.org/10.1152/jn.2002.88.3.1097.

[4] J.W. McChesney, M.H. Woollacott, The effect of age-related declines in proprioception and total knee replacement on postural control, Journals Gerontol. - Ser. A Biol. Sci. Med. Sci. 55 (2000) M658–M666. https://doi.org/10.1093/gerona/55.11.M658.

[5] T. Kimura, M. Kouzaki, Electrical noise to a knee joint stabilizes quiet bipedal stance, Gait Posture. 37 (2013) 634–636. https://doi.org/10.1016/j.gaitpost.2012.09.013.

[6] D.C. Gravelle, C.A. Laughton, N.T. Dhruv, K.D. Katdare, J.B. Niemi, L.A. Lipsitz, J.J. Collins, Noise-enhanced balance control in older adults, Neuroreport. 13 (2002) 1853–1856. https://doi.org/10.1097/00001756-200210280-00004.

[7] A.D. Likens, J.A. Kent, C.I. Sloan, S.R. Wurdeman, N. Stergiou, Stochastic Resonance Reduces Sway and Gait Variability in Individuals With Unilateral Transtibial Amputation: A Pilot Study, Front. Physiol. 11 (2020) 573700. https://doi.org/10.3389/fphys.2020.573700.

[8] A. Priplata, J. Niemi, M. Salen, J. Harry, L.A. Lipsitz, J.J. Collins, Noise-Enhanced Human Balance Control, Phys. Rev. Lett. 89 (2002) 3–6. https://doi.org/10.1103/PhysRevLett.89.238101.

[9] J.J. Collins, T.T. Imhoff, P. Grigg, Noise-enhanced tactile sensation, Nature. 383 (1996) 770. https://doi.org/10.1038/383770a0.

[10] J.J. Collins, A.A. Priplata, D.C. Gravelle, J. Niemi, J. Harry, L.A. Lipsitz, Noise-Enhanced Human Sensorimotor Function, IEEE Eng. Med. Biol. Mag. 22 (2003) 76–83. https://doi.org/10.1109/MEMB.2003.1195700.

[11] A.A. Priplata, B.L. Patritti, J.B. Niemi, R. Hughes, D.C. Gravelle, L.A. Lipsitz, A. Veves, J. Stein, P. Bonato, J.J. Collins, Noise-enhanced balance control in patients with diabetes and patients with stroke, Ann. Neurol. 59 (2006) 4–12. https://doi.org/10.1002/ana.20670.

[12] S. Zambrano, J.M. Casado, M.A.F. Sanjuán, Chaos-induced resonant effects and its control, Phys. Lett. A. 366 (2007) 428–432. https://doi.org/10.1016/j.physleta.2007.02.052.

[13] T.L. Carroll, L.M. Pecora, Stochastic Resonance and Crises, Phys. Rev. Lett. 70 (1993) 576–579. https://doi.org/10.1103/PhysRevLett.70.576.

[14] Richard D. Wilding, Chaos Theory: Implications for Supply Chain Management, Int. J. Logist. Manag. 9 (1998) 43–56.

[15] K. Itoh, T. Nakada, Human brain detects short-time nonlinear predictability in the temporal fine structure of deterministic chaotic sounds, Phys. Rev. E. 87 (2013) 1–6. https://doi.org/10.1103/PhysRevE.87.042916.

[16] K. Aghababaiyan, Improving performance of neurons by adding colour noise, IET Nanobiotechnology. 14 (2020) 433–439. https://doi.org/10.1049/iet-nbt.2019.0280.

[17] R. Soma, D. Nozaki, S. Kwak, Y. Yamamoto, 1/f Noise Outperforms White Noise in Sensitizing Baroreflex Function in the Human Brain, Phys. Rev. Lett. 91 (2003) 1–4. https://doi.org/10.1103/PhysRevLett.91.078101.

[18] C. Zippenfennig, L. Niklaus, K. Karger, T.L. Milani, Subliminal electrical and mechanical stimulation does not improve foot sensitivity in healthy elderly subjects, Clin. Neurophysiol. Pract. 3 (2018) 151–158. https://doi.org/10.1016/j.cnp.2018.10.001.

[19] P.E. Crago, P.H. Peckham, J.T. Mortimer, J.P. Van der Meulen, The choice of pulse duration for chronic electrical stimulation via surface, nerve, and intramuscular electrodes., Ann. Biomed. Eng. 2 (1974) 252–264. https://doi.org/10.1007/BF02368496.

[20] A. Tamura, M. Sonoo, S. Hoshino, T. Iwanami, H. Shimada, T. Miki, T. Shimizu, Stimulus duration and pain in nerve conduction studies, Muscle and Nerve. 47 (2013) 12–16. https://doi.org/10.1002/mus.23446.

[21] T. Kimura, M. Kouzaki, K. Masani, T. Moritani, Unperceivable noise to active light touch effects on fast postural sway, Neurosci. Lett. 506 (2012) 100–103. https://doi.org/10.1016/j.neulet.2011.10.058.

[22] R. Naruse, C. Taki, M. Yaegashi, Y. Sakaue, N. Shiozawa, T. Kimura, Attenuated spontaneous postural sway enhances diastolic blood pressure during quiet standing,

Eur. J. Appl. Physiol. 121 (2021) 251–264. https://doi.org/10.1007/s00421-020-04519-x.

[23] M. Kouzaki, K. Masani, H. Akima, H. Shirasawa, H. Fukuoka, H. Kanehisa, T. Fukunaga, Effects of 20-day bed rest with and without strength training on postural sway during quiet standing, Acta Physiol. 189 (2007) 279–292. https://doi.org/10.1111/j.1748-1716.2006.01642.x.

[24] T.E. Prieto, J.B. Myklebust, R.G. Hoffmann, E.G. Lovett, B.M. Myklebust, Measures of postural steadiness: Differences between healthy young and elderly adults, IEEE Trans. Biomed. Eng. 43 (1996) 956–966. https://doi.org/10.1109/10.532130.

[25] M. Yamagata, M. Popow, M.L. Latash, Beyond rambling and trembling: effects of visual feedback on slow postural drift, Exp. Brain Res. 237 (2019) 865–871. https://doi.org/10.1007/s00221-019-05470-w.

[26] M. Kouzaki, K. Masani, Reduced postural sway during quiet standing by light touch is due to finger tactile feedback but not mechanical support, Exp. Brain Res. 188 (2008) 153–158. https://doi.org/10.1007/s00221-008-1426-5.

[27] B.E. Maki, P.J. Holliday, G.R. Fernie, Aging and postural control. A comparison of spontaneous- and induced-sway balance tests, J. Am. Geriatr. Soc. 38 (1990) 1–9. https://doi.org/10.1111/j.1532-5415.1990.tb01588.x.

[28] A.O.O. Chan, M.H. Jim, K.F. Lam, J.S. Morris, D.C.W. Siu, T. Tong, F.H. Ng, S.Y. Wong, W.M. Hui, C.K. Chan, K.C. Lai, T.K. Cheung, P. Chan, G. Wong, M.F. Yuen, Y.K. Lau, S. Lee, M.L. Szeto, B.C.Y. Wong, S.K. Lam, Prevalence of

colorectal neoplasm among patients with newly diagnosed coronary artery disease, JAMA. 298 (2007) 1412–1419. https://doi.org/10.1001/jama.298.12.1412.

[29] J. Cohen, A power primer., Psychol. Bull. 112 (1992) 155–9. https://doi.org/10.1037//0033-2909.112.1.155.

[30] J. Milton, J.L. Cabrera, T. Ohira, S. Tajima, Y. Tonosaki, C.W. Eurich, S.A. Campbell, The time-delayed inverted pendulum: implications for human balance control, Chaos. 19 (2009) 026110. https://doi.org/10.1063/1.3141429.

[31] J.G. Milton, T. Ohira, J.L. Cabrera, R.M. Fraiser, J.B. Gyorffy, F.K. Ruiz, M.A. Strauss, E.C. Balch, P.J. Marin, J.L. Alexander, Balancing with vibration: A prelude for "drift and act" balance control, PLoS One. 4 (2009) 1–11. https://doi.org/10.1371/journal.pone.0007427.

[32] G.G. Simoneau, J.S. Ulbrecht, J.A. Derr, P.R. Cavanagh, Role of somatosensory input in the control of human posture, Gait Posture. 3 (1995) 115–122. https://doi.org/10.1016/0966-6362(95)99061-O.

[33] L. Thompson, M. Badache, S. Cale, L. Behera, N. Zhang, Balance Performance as Observed by Center-of-Pressure Parameter Characteristics in Male Soccer Athletes and Non-Athletes, Sports. 5 (2017) 86. https://doi.org/10.3390/sports5040086.

[34] K. Ueta, Y. Okada, H. Nakano, M. Osumi, S. Morioka, Effects of voluntary and automatic control of center of pressure sway during quiet standing, J. Mot. Behav. 47 (2015) 256–264. https://doi.org/10.1080/00222895.2014.974496.

[35] K.E. Costello, S.L. Matrangola, M.L. Madigan, Independent effects of adding weight and inertia on balance during quiet standing, Biomed. Eng. Online. 11 (2012) 1–13. https://doi.org/10.1186/1475-925X-11-20.

[36] K. Nosaka, A. Aldayel, M. Jubeau, T.C. Chen, Muscle damage induced by electrical stimulation, Eur. J. Appl. Physiol. 111 (2011) 2427–2437. https://doi.org/10.1007/s00421-011-2086-x.

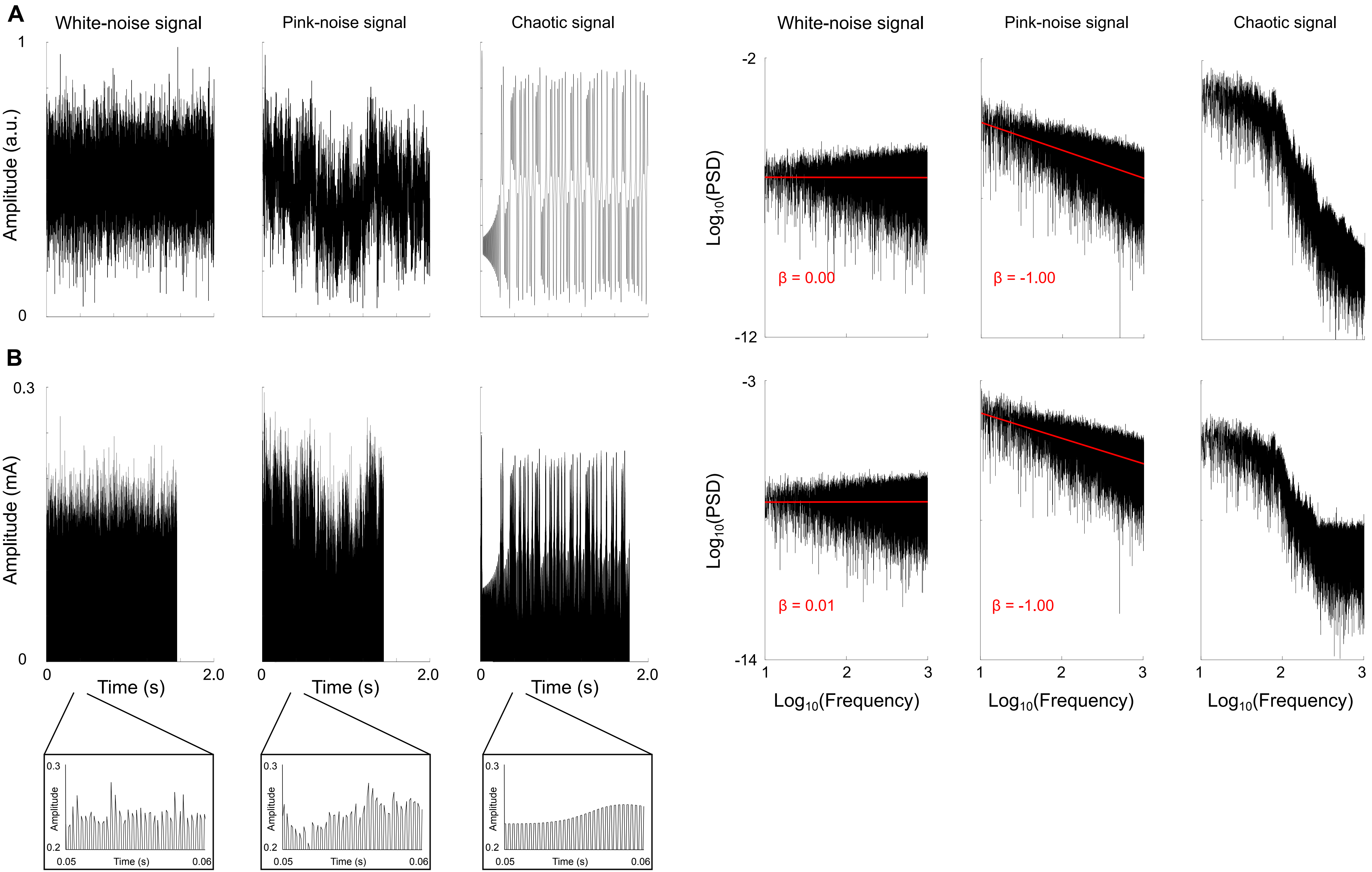
**Figure captions**

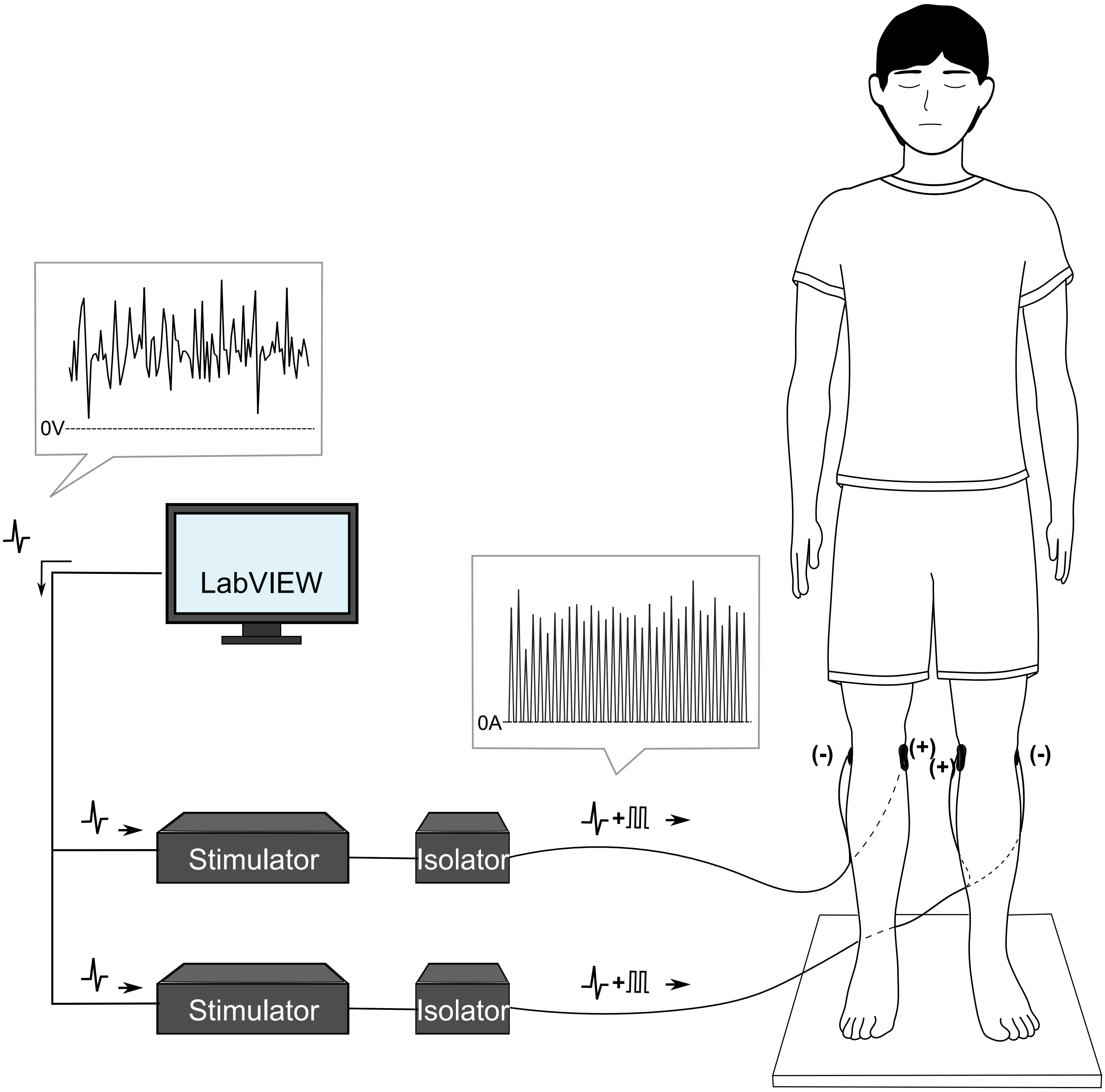
**Figure 1**. Examples of stimulation signals

A: The original signals and power spectral densities (PSDs) of white noise, pink noise, and chaotic signals generated by the MATLAB program are illustrated in the left and right panels, respectively. The PSDs are plotted on double logarithmic scales. The slopes for the white and pink noise signals are indicated by red lines with $\beta$ values. B: The modulated signals and corresponding power spectral densities for a typical participant.

**Figure 2**. Illustration of experimental setup

Stimulation electrodes were placed on the lateral and medial joint spaces of both knees, and the original noise or chaotic signal generated and output by the LabVIEW program was used for the electrical stimulation via isolators, after being combined with continuous square waves at two electrical stimulators.


A
White-noise signal
Pink-noise signal
Chaotic signal
1
0
Amplitude (a.u.)
White-noise signal
Pink-noise signal
Chaotic signal
-2
-12
Log10(PSD)
β = 0.00
β = -1.00
B
0.3
0
Amplitude (mA)
0
2.0
Time (s)
-3
-14
Log10(PSD)
β = 0.01
β = -1.00
1
2
3
Log10(Frequency)
0.3
0.2
Amplitude
0.05
Time (s)
0.06



0V
LabVIEW
0A
Stimulator
Isolator
Stimulator
Isolator
(-)
(+)
(+)
(-)

Table 1. Results of normalized CoP measures (%foot length)

| | No-Stim | WHITE | PINK | CHAOTIC |
|---|---|---|---|---|
| $CoP_{RMS}$ * | 1.62 (1.42-1.82) | 1.59 (1.40-1.92) | 1.31 (1.26-1.68) † | 1.58 (1.34-1.79) |
| $CoP_{MV}$($s^{-1}$) | 2.79 (2.36-3.17) | 2.68 (2.25-3.22) | 2.73 (2.09-3.18) | 2.94 (2.29-3.31) |
| $CoP_{Range}$ * | 7.98 (6.55-8.83) | 7.58 (6.62-9.30) | 6.66 (5.97-8.67) | 7.67 (6.37-8.63) |

Median (interquartile range)

CoP related measures normalized by foot length are shown for four simulation conditions: no stimulation (No-Stim), white-noise signal (WHITE), pink-noise signal (PINK), and chaotic signal (CHAOTIC).

$CoP_{RMS}$, root mean square of $CoP_{AP}$; $CoP_{MV}$, mean velocity of $CoP_{AP}$; $CoP_{Range}$, maximum amplitude of $CoP_{AP}$.

* Significant effects of *Stimulation* ($p < 0.05$); † Significant differences compared to No-Stim