Noise-Enhanced Human Balance Control

Attila Priplata,[1] James Niemi,[2] Martin Salen,[1] Jason Harry,[2] Lewis A. Lipsitz,[3] and J. J. Collins[1]

[1]*Center for BioDynamics and Department of Biomedical Engineering, Boston University, Boston, Massachusetts 02215*

[2]*Afferent Corporation, 194 Waterman Street, Providence, Rhode Island 02906*

[3]*Hebrew Rehabilitation Center for Aged, Department of Medicine of Beth Israel Deaconess Medical Center, Division on Aging, Harvard Medical School, Boston, Massachusetts 02215*

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Noise can enhance the detection and transmission of weak signals in certain nonlinear systems, via a mechanism known as stochastic resonance. Here we show that input noise can be used to improve motor control in humans. Specifically, we show that the postural sway of both young and elderly individuals during quiet standing can be significantly reduced by applying subsensory mechanical noise to the feet. We further demonstrate with input noise a trend towards the reduction of postural sway in elderly subjects to the level of young subjects. These results suggest that noise-based devices, such as randomly vibrating shoe inserts, may enable people to overcome functional difficulties due to age-related sensory loss.

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Noise, in any form, is normally thought of as interfering with signal detection and information transmission. Static on a radio station, ancillary conversations in a crowded room, and flashing neon lights along a busy thoroughfare all tend to obscure or distract from the desired information. But a wide range of studies in a variety of systems—including global climate models [1], electronic circuits [2], neurophysiological systems [3–11], perceptual systems [12–17], and behavioral systems [18–20]—have shown that certain levels of noise can enhance the detection and transmission of weak signals, via a mechanism known as stochastic resonance [21]. Here we show that input noise can be used to provide a functional benefit in human performance, namely, balance control.

Somatosensory feedback is an important component of the balance control system [22]. In this study, we examined the effects of noise input to the somatosensory system on posture control in humans. We hypothesized that the postural sway of both young and elderly individuals during quiet standing could be significantly reduced by applying mechanical noise to the feet. To test this hypothesis, we conducted a series of quiet-standing experiments on a healthy population of young and elderly subjects.

During the experiments, subjects stood comfortably on a platform with their eyes closed and hands at their side (Fig. 1). The platform was perforated (with a matrix of 48 holes in the anteroposterior direction and 41 holes in the mediolateral direction) allowing several hundred small nylon indentors (diameter $= 3.2$ mm), located under the plate, to pass through and touch the sole of each foot. The indentors were mounted onto two vertical linear actuators, one under each foot, in such a way that the displacement of the indentors into the skin was determined by the displacement of the actuators. Thus, two independent actuators transmitted their displacement and force to the indentors located under each foot. These mechanical actuators were controlled by two independent analog voltage signals generated by a computer. Uniform white noise signals, low-pass filtered to 100 Hz, were used.

At the outset of the testing session, each subject was asked to determine his or her threshold of tactile perception on the plantar surface of the foot. A potentiometer was used to adjust the amplitude of the noise signal driving each linear actuator. The subject was asked to adjust the potentiometer until he or she could no longer

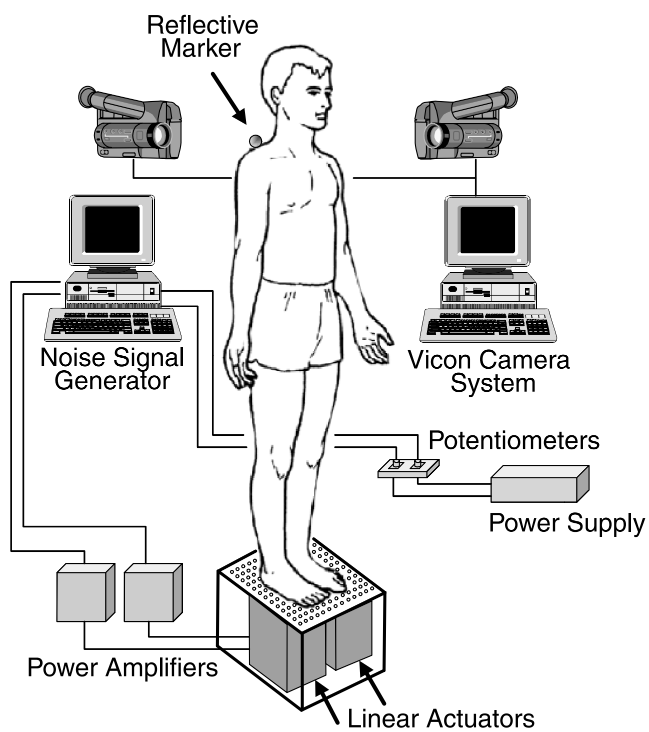

FIG. 1. A schematic diagram of the experimental setup.

feel the stimulation. The threshold for each foot was determined independently. The stimulation level for the experiments was set to 90% of this threshold level for each foot. Thus, the applied noise signals were subsensory, and subjects could not distinguish between noise and control trials.

An infrared reflective marker was attached to the right shoulder of each subject. A Vicon motion analysis system (Model 140, Oxford Metrics Ltd., Oxford, U.K.) was used to record the time-varying displacement of this marker during each 30-sec stance trial. A plot of the mediolateral (ML) and anteroposterior (AP) shoulder displacement, called a stabilogram, was produced and analyzed for each trial. For 14 young subjects (aged 21–26 years, mean 23 years; body mass 65.5–106.5 kg, mean 76.9 kg; height 160–192 cm, mean 176 cm), 20 trials were performed: 10 with mechanical noise presented to the sole of each foot and 10 without noise. For 16 elderly subjects (aged 67–83 years, mean 72 years; body mass 46.5 kg–90.7 kg, mean 67.3 kg; height 146–184 cm, mean 161 cm), 10 trials were performed: five with mechanical noise and five without noise. Only 10 trials (5 noise and 5 control) were performed on the elderly to reduce the effects of fatigue. The presentation sequence, noise or control, was pairwise randomized for each subject. All subjects took a two-minute seated break midway through the experiment.

To characterize balance during quiet standing, we used both traditional stabilogram analyses and random-walk analyses. Several traditional sway parameters were computed relative to the geometric center of the stabilogram for each trial: the mean stabilogram radius (mm), the area swept by the stabilogram over time (mm^2), the maximum radius of sway (mm), and the range of the AP and ML excursions (mm), respectively. We hypothesized that with the application of mechanical noise to the feet, there would be a reduction in postural sway, as indicated by decreases in these traditional measures.

The random-walk analysis yields a set of stabilogram parameters that can be related to the dynamics of the neuromuscular mechanisms underlying balance control [23]. The analysis is carried out by computing the mean square radial displacement $\langle \Delta r^2 \rangle$ as a function of time interval, a plot of which is known as a stabilogram-diffusion plot (Fig. 2). Stabilogram-diffusion plots are computed for each subject trial, and then these curves are averaged to obtain a resultant stabilogram-diffusion plot for a particular subject and test condition (e.g., noise vs control). Stabilogram-diffusion plots have two regions, one over short-term time intervals and one over long-term time intervals. These regions are separated by a critical period over which the slope of the plot changes considerably (Fig. 2). Three sets of posturographic parameters are extracted from these plots: effective diffusion coefficients, scaling exponents, and critical point coordinates (critical mean square displacement and critical time interval). The diffusion coefficients reflect the level of effective stochastic activity of the postural control system, and scaling exponents characterize the likelihood that the body will move away from or toward a relative equilibrium point. The critical point coordinates approximate the transition region separating the short-term and long-term regions.

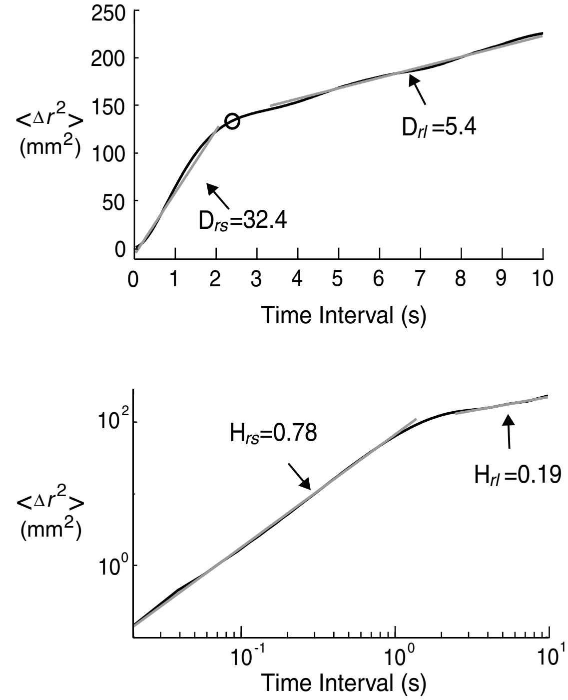

FIG. 2. Stabilogram-diffusion plots for a young subject. (Top) Linear-linear plot of the mean square radial displacement $\langle \Delta r^2 \rangle$ versus time interval. The short-term and long-term diffusion coefficients D_{rs} and D_{rl} (in units of mm^2 s^{-1}) are calculated from the slopes of the lines fitted to the short-term and long-term regions, respectively. The circle represents the critical mean square displacement $\langle \Delta r^2 \rangle_c$, which is determined from the first minimum of the second derivative of the stabilogram-diffusion plot. (Bottom) Log-log plot of the data shown in the top plot. The short-term and long-term scaling exponents H_{rs} and H_{rl} are calculated from the slopes of the lines fitted to the short-term and long-term regions, respectively.

In this study, we considered three random-walk sway parameters: the critical mean square displacement $\langle \Delta r^2 \rangle_c$ (mm^2), the effective long-term diffusion coefficient D_{rl} (mm^2 s^{-1}), and the long-term scaling exponent H_{rl}. In earlier studies on healthy young subjects [23], we found that over short-term time intervals during undisturbed stance the body sways as a positively correlated random walk (i.e., it tends to move or drift away from a relative equilibrium point), whereas over long-term time intervals it resembles a negatively correlated random-walk (i.e., it tends to return to a relative equilibrium point). We interpreted this finding as an indication that during quiet standing the postural control system utilizes open-loop and closed-loop control schemes over short-term and long-term time intervals, respectively. An open-loop control system is one which operates without sensory

TABLE I. Dimensionless values of the traditional and random-walk sway parameters for the control and noise trials for 30 subjects (14 young and 16 elderly). The group mean and standard error for each parameter are shown; p values for the comparison of the control and noise trials are also given.

Parameters	Control	Noise	p-Value
Mean radius	5.1 ± 0.3	4.7 ± 0.2	0.003[a]
Swept area	420.2 ± 34.0	396.1 ± 31.2	0.036[a]
Max radius	12.6 ± 0.6	12.2 ± 0.6	0.265
Range AP	20.7 ± 0.9	18.9 ± 1.1	0.024[a]
Range ML	13.1 ± 1.0	12.7 ± 0.8	0.377
$\langle \Delta r^2 \rangle_c$	48.5 ± 5.5	45.9 ± 5.4	0.179
D_{rl} (s^{-1})	1.9 ± 0.3	1.5 ± 0.2	0.060
H_{rl}	0.18 ± 0.02	0.15 ± 0.02	0.190

[a]Statistically significant ($p < 0.05$).

feedback, and in the case of the human postural control system may correspond to descending commands which set the steady-state activity levels of the postural muscles. Closed-loop control systems, on the other hand, operate with sensory feedback, and in the case of the human postural control system correspond to the visual, vestibular, and somatosensory systems [23].

Within this modeling framework, the critical mean square displacement $\langle \Delta r^2 \rangle_c$ characterizes the threshold at which feedback mechanisms are called into play by the postural control system, while D_{rl} and H_{rl} characterize the stochastic activity and antidriftlike dynamics, respectively, of these feedback mechanisms [23]. Note, a reduction in $\langle \Delta r^2 \rangle_c$ indicates a tendency to switch from open-loop postural control strategies to closed-loop postural control strategies at smaller excursions. A reduction in D_{rl} indicates a decreased tendency for random walking around a relative equilibrium point. Also, a reduction in H_{rl} indicates an increased tendency to return to a relative equilibrium point following a perturbation and thus corresponds to a more stable control system. Thus, in this study, we hypothesized that the addition of mechanical noise to the feet would lead to a reduction in the feedback threshold (as indicated by a decrease in $\langle \Delta r^2 \rangle_c$) and a more tightly regulated control system (as indicated by decreases in D_{rl} and H_{rl}).

Mean radius, maximum radius, range AP, and range ML for each subject were normalized to the height ($\times 10^{-3}$) of the reflective marker for each subject. Swept area, $\langle \Delta r^2 \rangle_c$, and D_{rl} were normalized to the height squared ($\times 10^{-6}$) of the reflective marker. For each parameter, we calculated the mean value for the control and noise trials, respectively, for each subject. Two-way repeated-measures analyses of variance (ANOVAs) were used to assess the main effects of stimulation (control vs noise) and age (elderly vs young) on postural sway and if interactions were present between stimulation and age ($p \leq 0.05$).

No interactions were found between stimulation and age in any of the parameters suggesting that there were no differential effects of mechanical noise in the elderly versus the young. Therefore, the main effects of stimulation and age were assessed. The results for the main effect of stimulation on traditional and random-walk sway parameters are presented in Table I. It can be seen that *all* of the parameters decreased with the application of noise. Note also that the decreases in mean radius, swept area, and range AP were statistically significant, while the reduction in D_{rl} approached significance.

Previous studies have shown that there are statistically significant differences in postural sway between the young and elderly (see [24] and references therein). Therefore, further analysis was done to compare the results from the elderly subjects with those from the young subjects. Specifically, we examined whether the traditional sway parameters in the elderly subjects decreased to levels of the young with the introduction of noise. Table II shows that each of the traditional sway parameters in the elderly with noise stimulation, especially mean radius and swept area, trend toward the control condition of young subjects. The random-walk parameters were expected to behave similarly to trends seen by Collins *et al.* [24]; i.e., in elderly, $\langle \Delta r^2 \rangle_c$ is higher, D_{rl} shows no difference, and H_{rl} is lower. As can be seen in Table II, parameters from the random-walk analysis confirm that

TABLE II. Dimensionless values of the traditional and random-walk sway parameters for the control and noise trials, averaged across the young and elderly subject populations. Group means and standard errors are shown.

	Young		Elderly	
Parameters	Control	Noise	Control	Noise
Mean radius	4.8 ± 0.3	4.5 ± 0.3	5.4 ± 0.4	5.0 ± 0.3
Swept area	410.2 ± 34.7	386.2 ± 36.8	429.0 ± 57.2	404.8 ± 49.9
Max radius	11.8 ± 0.7	11.3 ± 0.7	13.3 ± 0.8	12.1 ± 0.9
Range AP	18.9 ± 1.0	17.4 ± 1.2	22.3 ± 1.3	20.2 ± 1.7
Range ML	12.4 ± 1.2	11.9 ± 1.0	13.8 ± 1.5	13.5 ± 1.1
$\langle \Delta r^2 \rangle_c$	38.7 ± 4.9	36.8 ± 4.1	57.1 ± 8.9	53.8 ± 9.1
D_{rl} (s^{-1})	2.1 ± 0.4	1.5 ± 0.3	1.8 ± 0.4	1.5 ± 0.4
H_{rl}	0.21 ± 0.03	0.16 ± 0.02	0.15 ± 0.02	0.15 ± 0.03

elderly subjects, compared to young subjects, have higher feedback thresholds, approximately the same stochastic activity in their feedback mechanisms, and a greater likelihood after excursions to return to a relative equilibrium position.

In considering the significance of our results, it is important to note two points. First, because our study design consisted of making measurements on each subject under a control condition (i.e., no noise) and during an intervention (i.e., with noise), we applied a repeated-measures ANOVA to the mean parameter values for the control and noise trials, respectively, for each subject across the population. In doing so, we paired the control and noise results for each subject, which is in contrast to an ordinary ANOVA in which results are not paired. We thus expected the control results for a given subject to be closer to the noise results for that same subject than to the noise results for another subject randomly picked from the experimental population. As can be seen in Table I, we found the effects of the noise to be stronger, as indicated by the lower p values from the repeated-measures ANOVA, than would be expected from simply comparing the differences in group means relative to the variation across the group (as would be appropriate for an ordinary ANOVA, which was not appropriate for our study design). Second, it is interesting to note that the noise-induced changes in many of the sway parameters (Tables I and II) are of the same order as the differences found between the control conditions for the young and elderly subjects. Thus, in addition to statistical significance, our results may have significance from a motor control standpoint, in that the noise-enhancement effect may be sufficiently large to offset age-related declines in balance control.

This study shows that subsensory mechanical noise applied to the feet of quietly standing subjects leads to enhanced feedback and reduced postural sway. The mechanism underlying this finding is likely related to negative masking, which is a phenomenon in which the detectability of a weak stimulus is enhanced by the presence of another signal. Negative masking has been observed in vibrotactile sensation for cases wherein the test stimulus and the masker (or pedestal) are sinusoidal signals of the same frequency and phase [25]. Our results indicate that subthreshold noise, which is usually viewed as detrimental to signal detection, can be used as a suitable pedestal for enhancing the detection of pressure changes on the sole of the feet. This is important from a practical standpoint because noise can be used to enhance pressure sensation without knowing *a priori* the characteristics of the external stimuli, which is in contrast to the previous work with sinusoidal pedestals.

The trends observed in traditional sway parameters of older adults toward values seen in the young suggest that noise could ameliorate age-related impairments in balance control. It is possible that similar beneficial effects could be obtained in individuals with marked sensory deficits, such as patients with stroke or peripheral neuropathy [17]. In the future, noise-based devices, such as randomly vibrating shoe inserts, may enable people to overcome functional difficulties due to age- or disease-related sensory loss.

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