Human Balance out of Equilibrium: Nonequilibrium Statistical Mechanics in Posture Control

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During quiet standing, the human body sways in a stochastic manner. Here we show that the fluctuation-dissipation theorem can be applied to the human postural control system. That is, the dynamic response of the postural system to a weak mechanical perturbation can be predicted from the fluctuations exhibited by the system under quasistatic conditions. We also show that the estimated correlation and response functions can be described by a simple stochastic model consisting of a pinned polymer. These findings suggest that the postural control system utilizes the same control mechanisms under quiet-standing and dynamic conditions. [S0031-9007(97)05009-6]

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Nonequilibrium statistical mechanics [1–4] provides a theoretical framework for studying stochastic systems, a classic example being Brownian motion [5,6]. For many of these systems, there exists the fluctuation-dissipation theorem (FDT) [2–4,7–9], which provides a relationship between the correlations of the fluctuations of a system and its relaxation to equilibrium. Besides many applications in physics and chemistry, the FDT has been used to study protein dynamics [10], biochemical kinetics [11,12], and population risk mortality [13]. Here we apply the FDT to the human postural control system and use it to test the hypothesis that the system's dynamic response to a mechanical perturbation can be predicted from the fluctuations exhibited by the system under quasistatic conditions. Our specific aims are to show that (1) human postural sway is an equilibrium stochastic process for which the FDT holds, and (2) the response function and the derivative of the correlation function can be modeled by the analytical solution of the recently considered pinned-polymer model of posture control [14].

The human postural control system is highly complex—it involves multiple sensory systems and motor components. Numerous studies have investigated human balance control under quasistatic (unperturbed) conditions or dynamic (perturbed) conditions [15]. Despite these efforts, it remains unclear as to how the various sensorimotor components are integrated into the postural control system and whether the system utilizes similar mechanisms and strategies under quiet-standing and perturbed conditions [16].

Given the intrinsic complexity of the postural control system, it is not surprising that its output is highly irregular. For example, during quiet standing the center of pressure (COP) under an individual's feet continually fluctuates in a stochastic manner [see Fig. 1(b)]. Recently, Collins and De Luca [17,18] analyzed correlation functions $C(t - t') = \langle [y(t) - y(t')]^2 \rangle$ of quiet-standing COP time series and demonstrated that quasistatic postural sway can be represented as a correlated stochastic process. Motivated by these findings, Chow and Collins [14] proposed a pinned-polymer model to describe the stochastic dynamics of the human postural control system. This model is based on the assumption that the human body can be described by a continuum model analogous to a flexible string or polymer that is elastically pinned to an equilibrium position and under the influence of stochastic fluctuations. The motion of the COP is assumed to be represented by the motion of a single point along the polymer. The model can be justified given that (1) the human body in an upright stance is able to assume an infinite number of possible geometric configurations in equilibrium with external forces [17], and (2) the force output of skeletal muscles is noisy [19]. We model the dynamics in one spatial dimension $y(z,t)$ with a Langevin equation [14]

$$\beta \partial_t^2 y + \partial_t y - \nu \partial_z^2 y + \alpha y = \eta(z,t), \qquad (1)$$

where the parameter β represents the onset-of-damping time scale, α^{-1} represents the onset-of-pinning time scale, and ν is an effective tension parameter. The stochastic driving force $\eta(z,t)$ is assumed to be uncorrelated, i.e., $\langle \eta(z,t)\eta(z',t')\rangle = 2D\,\delta(t - t')\delta(z - z')$. Similar dynamics occur in widespread areas of physics, such as the surface variations of a granular aggregate [20], the dynamic fluctuations of growing interfaces [21], and the kinetic theory of flux-line hydrodynamics [22].

Equation (1) obeys the FDT, which relates the linear response function to the correlation function [2,3,7]. If we add a perturbation in the form of a spatiotemporal δ distribution $\epsilon(z,t) = \epsilon\delta(t - t')\delta(z - z')$ to the right-hand side of Eq. (1), we can obtain the Fourier transform of the response function $R(z,t) \equiv \langle \delta y / \delta \epsilon \rangle$ [14]

$$\tilde{R}(k,\omega) = \frac{1}{-\beta\omega^2 - i\omega + \alpha + \nu k^2}. \qquad (2)$$

The power spectrum $S(k,\omega)$ of $y(z,t)$, which is the Fourier transform of the correlation function $S(z,t) = \langle y(z,t)y(0,0)\rangle$, is given by [14]

$$S(k,\omega) = \frac{2D}{|-\beta\omega^2 - i\omega + \alpha + \nu k^2|^2}. \quad (3)$$

Equations (2) and (3) immediately give $\mathrm{Im}\,\tilde{R}(k,\omega) = i\omega/2DS(k,\omega)$. Assuming causality, this leads in the time domain to the relation

$$R(k,t) = -\frac{1}{D}\frac{dS(k,t)}{dt}, \qquad t > 0, \quad (4)$$

which is the FDT for the pinned-polymer model. In our experimental measurements, we consider the quantity $C(t) = 2[S(z,0) - S(z,t)]$, where $z \equiv \text{const} = 0$. This leads to the relation $R(t) = 1/(2D)\, dC(t)/dt$.

In our experiments, COP time series were recorded from ten healthy young subjects. Subjects were studied under quiet-standing and dynamic conditions (Fig. 1). During each dynamic test, a weak mechanical perturbation was applied to the subject's pelvis. An estimate for the response function, $\hat{R}(t)$, was calculated by averaging the 20 perturbed trials, using the time of the maximal-sway amplitude following the perturbation as a trigger point. Each trial was normalized to unity at the trigger point. The derivative of the correlation function, $\widehat{dC}(t)/dt$, was obtained by estimating the autocorrelation function $S(t)$ [23] of each unperturbed trial, calculating its derivative (using a simple filter), averaging the resulting single-trial estimations, and multiplying by -1. As above, the time of the maximal-sway amplitude of each trial was used as the trigger point for the averaging, and each trial was normalized by its trigger-point amplitude prior to averaging.

Figure 2 displays the results for $\hat{R}(t)$ and $\widehat{dC}(t)/dt$ for two subjects. It can be seen that $\hat{R}(t)$ and $\widehat{dC}(t)/dt$ were well matched for the first 4 s. We quantified the ability to predict one curve from the other by a linear regression [i.e., by fitting $\hat{R}(t) = a + b(\widehat{dC}(t)/dt)$] with errors in variables [24,25]. The errors in each time point were estimated by the standard deviation of the mean of the single trials. (Note that the numerical results of the parameters a and b are not of interest since a only reflects that there is an arbitrary zero COP, i.e., an undefined coordinate origin in the perturbed trials, and b has an arbitrary unit due to the normalization of all trials.) The goodness of the fit over the first 400 points (4 s) was judged [26] by the estimated $\hat{\chi}^2$ quantity, which is the sum of squared residuals weighted by the errors in both data sets [25]. In seven of the ten subjects, this test clearly indicated that the two curves were significantly well matched—the $\hat{\chi}^2$ values were between 300 and 480. (In the three other subjects, the $\hat{\chi}^2$ values were 820, 940, and 1100, respectively, indicating that the curves were not significantly well matched.) Thus, in the majority of cases, we were able to predict the general behavior of $\hat{R}(t)$ (which was estimated from the perturbed trails) from $\widehat{dC}(t)/dt$ (which was obtained from the quiet-standing trials).

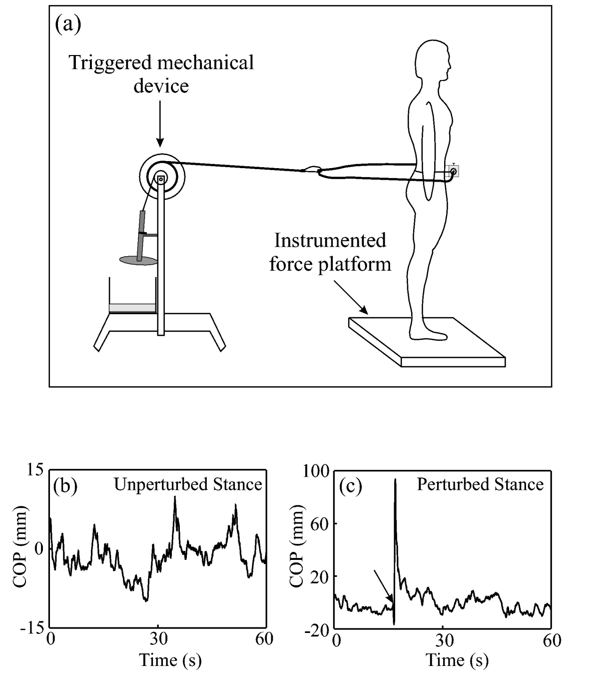

FIG. 1. (a) A schematic diagram of the experimental setup. A Kistler 9287 force platform was used to record the time-varying anteroposterior displacements of the center of pressure (COP) under the feet of the subjects. (See Ref. [17] for additional details.) Ten healthy young subjects (five females and five males; age: 19–29 years; height: 162–188 cm; weight: 54–87 kg) were included in the study. Each subject was instructed to stand quietly and relaxed in an upright posture on the platform. Three sets of 10 trials were conducted on each subject: 10 unperturbed trials of 90 s duration each and 20 perturbed trials of 60 s duration each. Perturbations (of $\sim$7.35 N m) were applied (randomly in a range between 15 and 20 s after the initiation of a trial) in the backward direction to each subject's pelvis by a triggered mechanical device. Subjects were not provided with any precues about the occurrence of the perturbation. (b) A 60 s sample of a typical COP times series for a quiet-standing trial. (c) A typical COP time series for a perturbed trial; the arrow marks the time at which the perturbation was applied.

We also fit, by a Levenberg-Marquardt algorithm [26], $\hat{R}(t)$ and $\widehat{dC}(t)/dt$ to the analytically calculated response function for the pinned-polymer model (for a spatiotemporal δ distribution) [14]

$$R(t) = \Theta(t)\,\frac{e^{-t/2\beta}}{2\sqrt{\nu\beta}}\, J_0\!\left(\frac{\sqrt{4\alpha\beta - 1}}{2\beta}\, t\right), \quad (5)$$

where Θ is the step function and $J_0(x)$ is the zeroth-order Bessel function. For $4\alpha\beta < 1$, J_0 is replaced by the zeroth-order modified Bessel function I_0. We made the assumption that the estimated standard deviations displayed in Fig. 2 are normally distributed. In this case, the errors for the parameters of the fitted functions can be obtained from the covariance matrix of the fit [26].

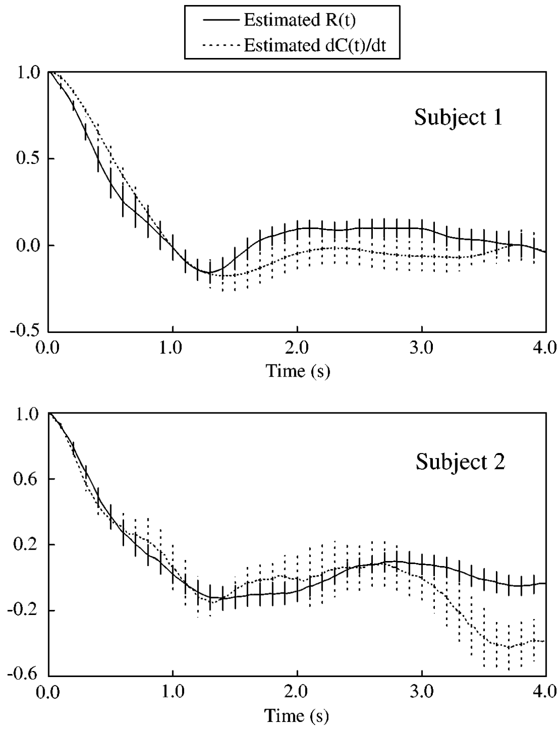

FIG. 2. Estimated response functions $\hat{R}(t)$ (solid lines) and derivatives of the correlation functions $\widehat{dC}(t)/dt$ (dotted lines) for two subjects. The error bars (plotted on every tenth point) represent the standard error of the mean of the single-trial estimations. For the two subjects shown, the estimated $\hat{\chi}^2$ quantities for the fit $\hat{R}(t) = a + b\,(\widehat{dC}(t)/dt)$ (see text) are $\hat{\chi}^2 = 340$ (subject 1) and $\hat{\chi}^2 = 371$ (subject 2), indicating that in each case one can linearly predict one function from the other.

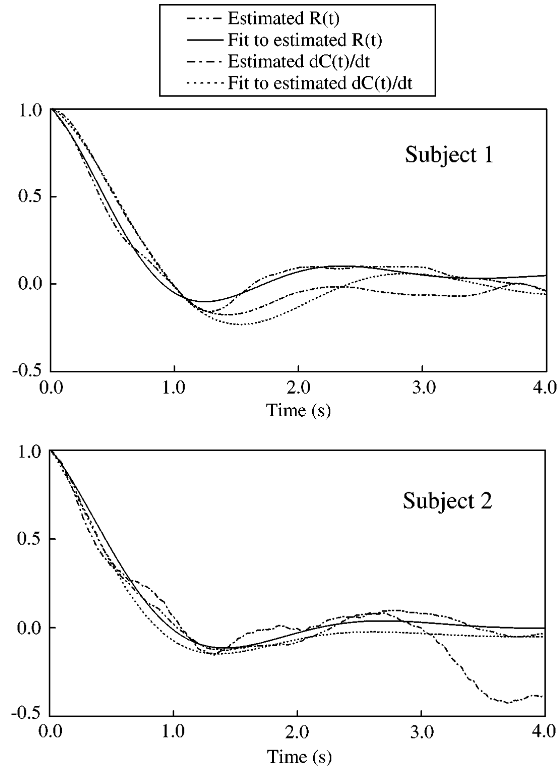

FIG. 3. Results of the fit of $\hat{R}(t)$ and $\widehat{dC}(t)/dt$, respectively, to the pinned-polymer posture model Eq. (5) for the two subjects of Fig. 2. Since one is unable to define a "mean" or "zero" position in the perturbed trials, an arbitrary dc offset is present. To account for this offset, we fit a fourth "dc" parameter to Eq. (5), which corresponded simply to adding a constant to the equation. Therefore, the zero level in each plot does not correspond to the equilibrium state. Note that for subject 1, who exhibited a more "oscillating" behavior, the parameter α was approximately twice as large as that for subject 2.

The goodness of the fit was again estimated using a χ^2 statistic. In nine of the ten subjects, we obtained good fits for both $\hat{R}(t)$ and $\widehat{dC}(t)/dt$ (e.g., see Fig. 3). These results indicate that the model holds for the majority of subjects.

These novel results demonstrate that the dynamics observed in human postural sway can be described by an equilibrium stochastic process for which the FDT applies and that the proposed pinned-polymer model well describes the correlation and response functions of the data. The existence of the FDT (which does not necessarily imply that the stochastic process is linear [9]) leads to physiological conclusions that are independent of the analytical model. One such conclusion is that if the postural control system at a time t_0 is in a nonequilibrium state, then it cannot distinguish whether it was brought into that state by an external, perturbating force or an intrinsic, random fluctuation. From a physiological standpoint, this implies that the postural control system may use the same neuromuscular control mechanisms under quiet-standing and dynamic conditions.

The discrepancy between the response and correlation functions found in three of the ten subjects may have been due to compensatory or learned strategies that were adopted by the subjects during the experiments. For example, if a subject voluntarily introduced a compensatory movement during a trial, this would appear as an independent, nonstationary, biased perturbation acting on the system. If this were the case, then the FDT, which is assumed to hold without such "additional fluctuations," would not be seen in the associated response and correlation functions.

The response function should exhibit a dynamical structure for times as long as 20–30 s after a perturbation, since this is the longest time over which significant correlations are found in quiet-standing postural-sway data [17,18]. (Physiologically, this means that the postural control system takes 20–30 s to recover fully from a weak perturbation.) However, the data, in general, only showed strong observance of the FDT for relatively short times (e.g., <4 s). This result is likely due, in part, to the nonstationary effects of voluntary movements (as mentioned above) and the sensory feedback systems which act on the body. It is also related to the fact that as the response function approaches zero the signal-to-noise ratio of the data worsens, so the points become more unreliable as one goes to longer times. We are limited in the amount of averaging that can be done since, during long trials, subjects tire and the system changes. Under such circumstances, we cannot obtain reliable results. Note that the long correlation times mentioned above are not in contradiction to the 4 s for which the FDT holds. The response and correlation functions are nonparametric estimations from empirical data. Therefore, it might be that $\hat{R}(t)$ and $\widehat{dC}(t)/dt$ deviate after a few seconds for the above reasons, but $\hat{C}(t)$ and $\hat{R}(t)$ both exhibit some significant, but different dynamical structure.

From a clinical standpoint, this work suggests that it may be possible to use the FDT to predict the impairment of the postural control system under dynamic conditions from data recorded in quiet-standing experiments. Such a development would simplify and improve clinical balance testing by eliminating the need for introducing potentially deleterious perturbations to frail patients.

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[1] I. Prigogine, *Non-equilibrium Statistical Mechanics* (John Wiley & Sons, New York, 1962).
[2] R. Balescu, *Equilibrium and Nonequilibrium Statistical Mechanics* (John Wiley & Sons, New York, 1975).
[3] J. Honerkamp, *Stochastic Dynamical Systems* (VCH, New York, 1994).
[4] B. Gaveau and L. S. Schulman, J. Math. Phys. (N.Y.) **37**, 3897 (1996).
[5] J. Klafter, M. F. Shlesinger, and G. Zumofen, Phys. Today **49**, No. 2, 33 (1996).
[6] R. D. Astumian, Science **276**, 917 (1997).
[7] H. Risken, *The Fokker-Planck Equation: Methods of Solution and Applications* (Springer-Verlag, New York, 1989), 2nd ed.
[8] U. Deker and F. Haake, Phys. Rev. A **11**, 2043 (1975).
[9] B. J. West and K. Lindenberg, in *Fluctuations and Sensitivity in Nonequilibrium Systems,* edited by W. Horsthemke and D. K. Kondepudi (Springer-Verlag, Berlin, 1969), pp. 233–241.
[10] W. Doster, Biophys. Chem. **17**, 97 (1983).
[11] P. Erdi and L. Ropolyi, Biol. Cybernet. **32**, 41 (1979).
[12] G. Jannink, B. Duplantier, and J. L. Sikorav, Biophys. J. **71**, 451 (1996).
[13] M. O. Vlad, B. Schonfisch, and M. C. Mackey, Phys. Rev. E **53**, 4703 (1996).
[14] C. C. Chow and J. J. Collins, Phys. Rev. E **52**, 907 (1995).
[15] V. Dietz, Physiol. Rev. **72**, 33 (1992).
[16] H. C. Diener, J. Dichgans, B. Guschlbauer, and M. Bacher, Hum. Neurobiol. **5**, 105 (1986); F. B. Horak and L. M. Nashner, J. Neurophysiol. **55**, 1369 (1986); M. H. Woollacott, C. van Hosten, and B. Rösblad, Exp. Brain Res. **72**, 593 (1988); S. P. Moore, D. S. Rushmer, S. L. Windus, and L. M. Nashner, *ibid.* **73**, 648 (1988); F. B. Horak, L. M. Nashner, and H. C. Diener, *ibid.* **82**, 167 (1990).
[17] J. J. Collins and C. J. De Luca, Exp. Brain Res. **95**, 308 (1993); **103**, 151 (1995).
[18] J. J. Collins and C. J. De Luca, Phys. Rev. Lett. **73**, 764 (1994).
[19] G. C. Joyce and P. M. H. Rack, J. Physiol. **240**, 375 (1974).
[20] S. F. Edwards and D. R. Wilkinson, Proc. R. Soc. London A **381**, 17 (1982).
[21] M. Kardar, G. Parisi, and Y.-C. Zhang, Phys. Rev. Lett. **56**, 889 (1986).
[22] L. Radzihovsky and E. Frey, Phys. Rev. B **48**, 10 357 (1993).
[23] P. J. Brockwell and R. A. Davis, *Time Series: Theory and Methods* (Springer-Verlag, New York, 1991).
[24] W. A. Fuller, *Measurement Error Models* (John Wiley & Sons, New York, 1987).
[25] J. H. Williamson, Can. J. Phys. **46**, 1845 (1968).
[26] W. Press, B. Flannery, S. Saul, and W. Vetterling, *Numerical Recipes* (Cambridge University Press, Cambridge, MA, 1992), 2nd ed.