

Predicting the dynamic postural control response from quiet-stance behavior in elderly adults

Elizabeth T. Hsiao-Wecksler^{a,*}, Kunal Katdare^a, Jennifer Matson^a, Wen Liu^{a,b}, Lewis A. Lipsitz^c, James J. Collins^a

^aDepartment of Biomedical Engineering, Center of BioDynamics, Boston University, Boston, MA, USA

^bDepartment of Physical Therapy Education, University of Kansas Medical Center, Kansas City, KS, USA

^cHebrew Rehabilitation Center for Aged, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, MA, USA

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Abstract

Human postural sway, as measured by fluctuations of the center of pressure (COP) under the feet of a quietly standing individual, can be characterized as a stochastic process. The fluctuation–dissipation theorem (FDT) provides a linear relationship between the fluctuations of a quasi-static, stochastic system to the same system's relaxation to equilibrium following a perturbation. We applied a similar linear relationship, based on the FDT, to the human postural control system to explore whether anterior–posterior (AP) fluctuations of the COP during quiet stance can be used to predict the AP response of the postural control system to a weak posteriorly directed mechanical perturbation (tug or pull at the waist). We tested 10 healthy elderly (mean age of 69 yr) and 10 healthy young (mean age of 25 yr) adult subjects. We found that this linear relationship was applicable to the postural control system of all 10 young and eight of the 10 elderly adult subjects. These results suggest that it is possible to predict an individual's dynamic response to a mild perturbation using quiet-stance data, regardless of age. The existence of this FDT-based linear relationship with respect to the human postural control system suggests that, for a given individual, the postural control system may use the same control mechanisms during quiet stance and mild-perturbation conditions, regardless of age.

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1. Introduction

Human postural control during upright stance is typically assessed in either of two modes: (1) quiet stance, i.e., stance with no intended movement (a “quasi-static” condition), or (2) perturbed stance, i.e., quiet stance that is disturbed by an external perturbation, such as a push at the sternum or a sudden shift of the support surface (a “dynamic” condition). Tests involving perturbations could involve potential safety risks, especially for persons with impaired balance such

as elderly adults. Clinically, if it were possible to predict an individual's response to a perturbation using quiet-stance data, then it would be unnecessary to perform potentially hazardous perturbation tests in order to assess an individual's postural control capacity.

Fluctuations in the center of pressure (COP) under the feet of an individual during quiet standing can be represented as a stochastic process (Chiari et al., 2000; Chow and Collins, 1995; Collins and De Luca, 1993,1994,1995; Ohira and Milton, 1995; Peterka, 2000; Sabatini, 2000; Yao et al., 2001). A statistical mechanics theorem that applies to many stochastic systems is the fluctuation–dissipation theorem (FDT) (Honerkamp, 1998; Kubo, 1966; Pathria, 1972). The FDT links the intrinsic fluctuations of a quasi-static system to the system's dynamic response to an external perturbation. More specifically, it provides a linear relationship between the decay of correlations in the

*Corresponding author. Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign, 140 Mechanical Engineering Building MC-244, 1206 West Green Street, Urbana, IL 61801, USA. Tel.: +1-217-333-3415; fax: +1-217-244-6534.

E-mail address: ethw@uiuc.edu (E.T. Hsiao-Wecksler).

URL: <http://cbd.bu.edu/abl/>.

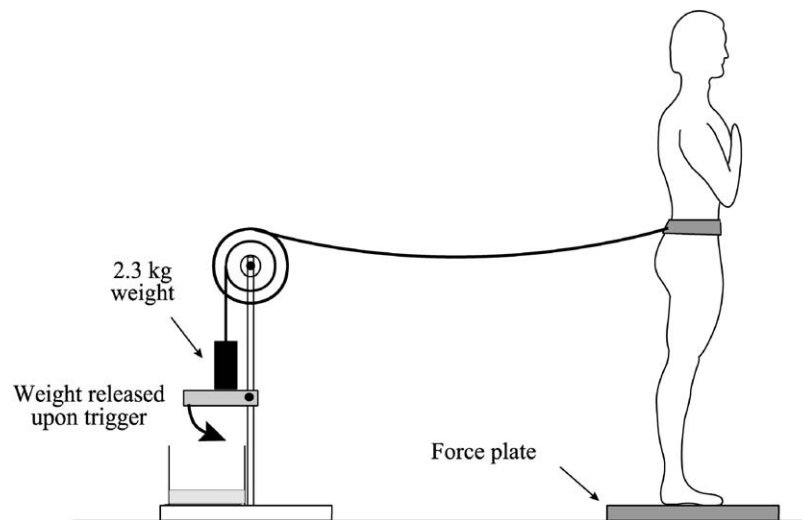


Fig. 1. Experimental setup. Each subject stood with eyes open and bare feet on a force plate (model 9286, Kistler Instrument Corp., Amherst, NY). The subject was loosely tethered at the waist to the perturbation mechanism such that normal postural sway was unhindered. To initiate a perturbation, a mechanical trigger was activated that released a weight, which caused a small backward tug.

fluctuations of a stochastic system during a quasi-static condition and the system's relaxation to equilibrium following a perturbation.

Lauk et al. (1998) applied a linear relationship based on the FDT to the human postural control system. By conducting quiet- and perturbed-stance experiments, they were able to show in young adult subjects that anterior–posterior (AP) fluctuations of the COP during quiet stance can be used to predict the AP response of the dynamic postural control system to a weak posteriorly directed perturbation through a linear relationship. They also concluded that, since this FDT-based linear relationship held for these conditions, the postural control system uses the same neuromuscular control mechanisms during quiet-standing and mild-perturbation conditions. These results suggest that, at least with healthy young adults, it may be possible to both assess postural control capacity and explore neuromuscular control behavior in response to mild-perturbations using a simple, non-stressful technique based on quiet standing. However, it is not known whether this technique can be applied to older adults and/or individuals with impaired balance control.

Aging is associated with alterations in postural control and response to perturbations (Collins et al., 1995; Horak et al., 1989). It is also associated with an increased risk for falls during perturbations (Sattin, 1992). A variety of integrated physiological systems have also been shown to demonstrate a breakdown in dynamic behavior with advancing age (Lipsitz, 2002). These age-related alterations suggest that, in contrast to young adults, the control mechanisms during quiet and perturbed stance may be different in older adults. Thus, this FDT-based linear relationship might not be applicable to the postural control system for this group.

Accordingly, we hypothesized that it would not be possible to predict the dynamic response of the postural control system to a weak perturbation from quiet-standing data in elderly individuals.

2. Methods

2.1. Subjects

We tested two groups of healthy, community-dwelling adult subjects: 10 elderly (five females and five males; age range: 66–73 yr, mean age: 69 ± 2 (SD) yr; weight: 53–81 kg; height: 1.5–1.7 m) and 10 young adults (five females and five males; age range: 21–30 yr, mean age: 25 ± 3 yr; weight: 51–89 kg; height: 1.6–1.8 m). Community-dwelling elderly subjects were recruited from the Harvard Cooperative Program on Aging Subject Registry. Subjects were excluded if they had a gait, orthopaedic, or neuromuscular impairment. The study was approved by the Institutional Review Board of Boston University. Informed consent was obtained from each subject.

2.2. Experimental procedures

Twenty randomized trials were conducted on each subject: 10 quiet-standing trials and 10 perturbed trials, all 30 s in duration. For all 20 trials, the subject was instructed to maintain a quiet, upright posture throughout the recording (Fig. 1). To initiate a perturbation, which was a weak impulse disturbance (a backward tug), a mechanical trigger was activated that released a 2.3 kg mass. After the weight fell, the perturbation mechanism caused the tether to quickly slacken, thus

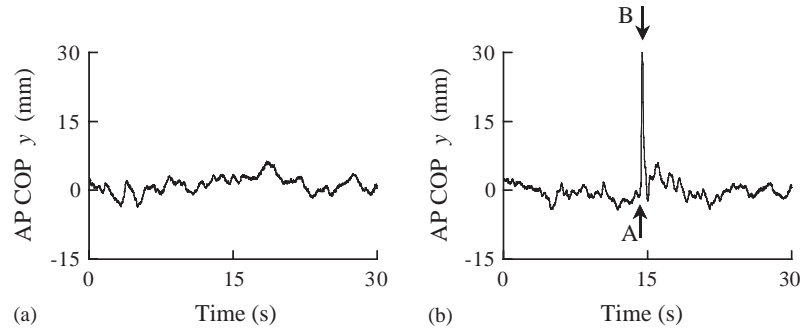


Fig. 2. A typical 30 s anterior–posterior COP times series, y , for (a) a quiet-stance trial and (b) a perturbed-stance trial. Arrow A indicates application of the backward tug. Arrow B indicates peak backward sway. Positive values indicate displacements toward the posterior direction, while negative values indicate displacements toward the anterior direction.

allowing the subject to adjust to an upright posture. The tug necessitated only a postural sway response, i.e., the subject did not need to take a step to maintain balance. The trigger was activated after a random delay of 10–20 s from the start of the trial. The subject received no cues as to if or when the perturbation would occur. For all trials, the COP time series data in the AP (y) direction was computed from force-plate measurements, which were sampled at 120 Hz. To account for variability of foot placement relative to the force-plate origin, each 30 s trial (3600 points) was adjusted such that the COP trajectory was centered about the mean value of the first 9 s (1080 points) of the time series. This adjusted time series, y , was calculated by referencing the original time series, y_0 , respectively, to this mean value, e.g., for datapoint i :

$$y(i) = y_0(i) - \frac{1}{N} \sum_{j=1}^N y_0(j),$$

where $i = 1$ to 3600 and $N = 1080$. These data were then filtered with a tenth order, 20 Hz low pass finite impulse response (FIR) digital filter.

2.3. FDT-based analysis

The AP fluctuations of the COP during both quiet- and perturbed-stance trials (Fig. 2) were analyzed using a linear regression based on the FDT. The response function ($R(t)$) of the AP displacement of the COP to a mild backward tug was related to the derivative of a correlation function ($dC(t)/dt$) based on AP fluctuations of the COP during quiet standing.¹ That is, assuming the FDT is applicable to the postural control system, then

$$R(t) = a + b(dC(t)/dt), \quad (1)$$

¹Using the pinned-polymer model of postural control proposed by Chow and Collins (1995), Lauk and colleagues (1998) suggested that the FDT for this model would be $R(t) = (1/2D)(dC(t)/dt)$, where $2D$ is the amplitude of a stochastic driving force on the polymer.

where a is typically small and reflects an arbitrary origin for the COP,² and b has arbitrary units due to normalization of all trials. We computed $dC(t)/dt$ and $R(t)$ for each subject using a procedure described previously (Lauk et al., 1998).

In summary, for the quiet-standing trials, we first determined the autocorrelation of y for the k th trial $S_k(\tau) = \langle y_k(t)y_k(t + \tau) \rangle$, where τ represents a time delay and $\langle \cdot \rangle$ denotes ensemble average (Fig. 3a). We then calculated the correlation function $C_k(t) = 2[\text{var}(y_k(t)) - S_k(t)]$, where $\text{var}(y_k(t))$ is the variance of y for trial k . Then we computed the derivative $dC_k(t)/dt$. The time of the maximal amplitude of $dC_k(t)/dt$ was used as the trigger point. Each trial was normalized in amplitude to unity at the trigger point. A 4 s window of data beginning from the trigger point was then selected.³ Results of the 4 s windows from all quiet-stance trials for a given subject were combined to obtain the average derivative of the correlation function $dC(t)/dt$ (Fig. 3a).

The dynamic response function to the perturbation $R(t)$ was calculated by averaging AP (y) data from all 10 trials. For each perturbed trial, the time of the peak backward sway amplitude following the perturbation was used as the trigger point (Fig. 2b, Point B). Each trial was normalized to unity at the trigger point, and a 4 s window of data was selected. Results of the 4 s windows from all perturbation trials were averaged to obtain $R(t)$ (Fig. 3b).

Finally, the predicted response $R_p(t)$ was computed from $R_p(t) = \hat{a} + \hat{b}(dC(t)/dt)$, where \hat{a} and \hat{b} are the optimal estimates for the parameters a and b , respectively. The cost function, used to determine \hat{a} and \hat{b} , was based on fitting Eq. (1) to the experimental data using the method of least squares with errors in both variables (Williamson, 1968), and minimized with the simulated

²Since a is non-zero, Eq. (1) represents a modified version of the FDT with perhaps non-stationary drift.

³Lauk et al. (1998) found that, in general, strong observance of the FDT-based relationship could only be shown for the first 4 s of data.

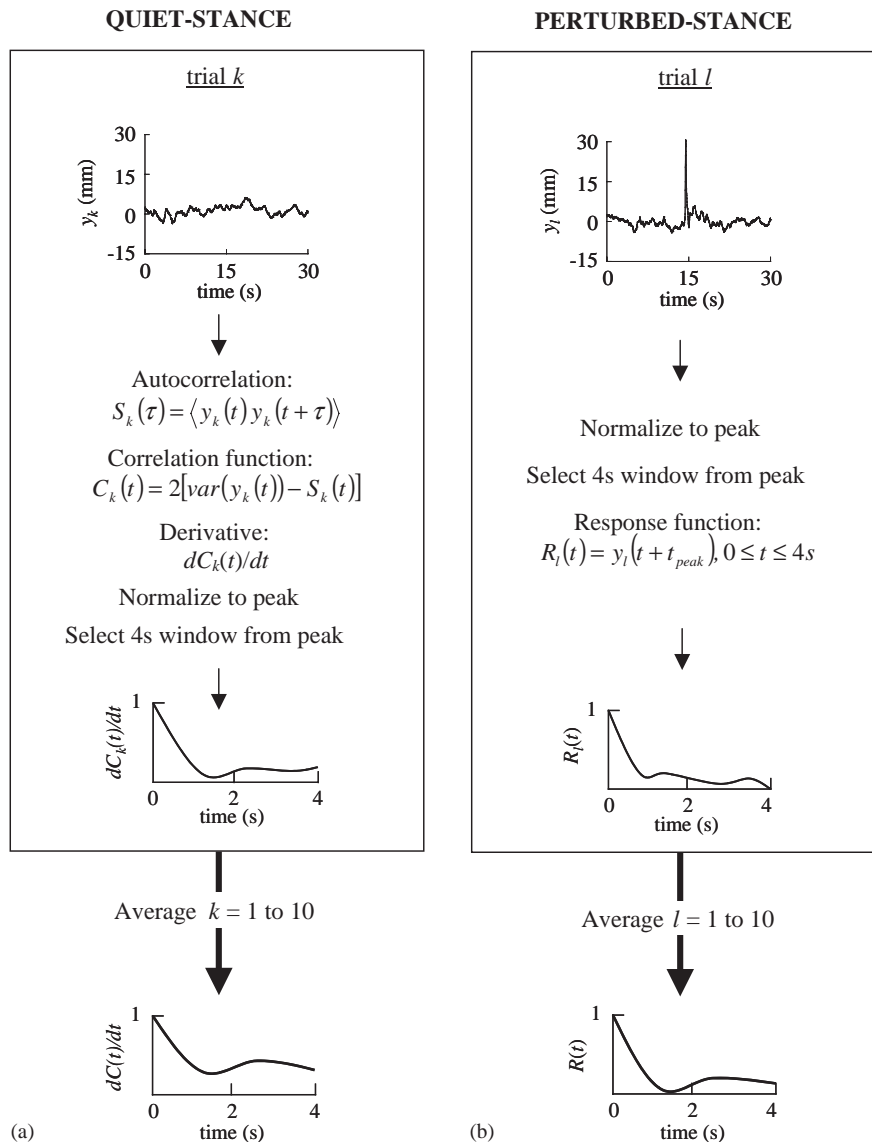


Fig. 3. Flowcharts of the data analysis protocols used to compute $dC(t)/dt$ and $R(t)$ for each subject. (a) For each quiet-stance trial k , the autocorrelation of y_k , $S_k(\tau)$, and correlation function, $C_k(t)$, were determined. Then the derivative of the correlation function, $dC_k(t)/dt$, was computed and normalized to unity by the peak amplitude. A 4 s window starting from this peak value was selected. Finally, the results from all trials were averaged together to determine $dC(t)/dt$. (b) For each perturbed-stance trial l , the data were normalized to unity by the peak backward sway amplitude. The response function, $R_l(t)$, was selected as the 4 s window from this peak sway value. Finally, the average response function, $R(t)$, was computed.

annealing algorithm (Press et al., 1989). To test whether the FDT-based relationship held for the postural control system of a given subject, the goodness-of-fit between the actual and predicted dynamic response functions, $R(t)$ and $R_p(t)$, respectively, was evaluated by a χ^2 test statistic with $P-Q$ degrees of freedom, where P is the number of data points (i.e., 480, due to a 4 s window at 120 Hz) and Q is the number of adjustable parameters (i.e., 2, due to $R(t)$ and $dC(t)/dt$) (Williamson, 1968). Therefore, $\chi^2 = 478$ represents a moderately good fit, and χ^2 decreases as the fit between $R(t)$ and $R_p(t)$ improves.

2.4. Supplemental balance parameters

To compare balance or postural stability characteristics of each test group, supplemental COP parameters were computed from quiet-stance data using techniques from both (a) stabilogram-diffusion analysis and (b) more commonly reported or traditional sway analysis procedures. Stabilogram-diffusion analysis (Collins and De Luca, 1993; Collins et al., 1995) uses random walk analyses to describe the behavior of the COP during short-term s and long-term l intervals of time with three repeatable sets of parameters, i.e., diffusion coefficients

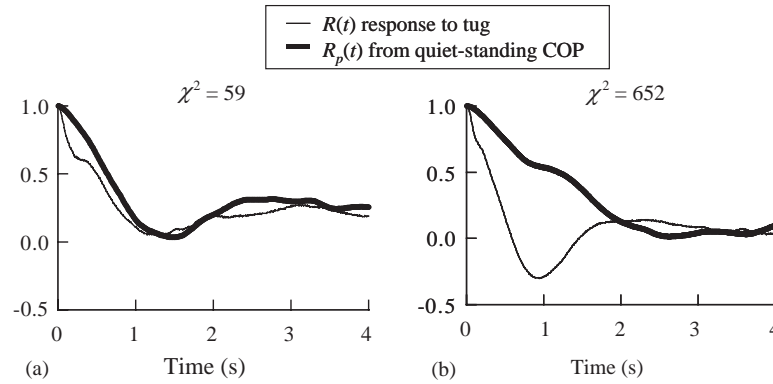


Fig. 4. Sample results from the FDT-based analysis for two subjects. The goodness-of-fit of the actual (thin line) versus predicted (bold line) response function is tested using the χ^2 test statistic with 478 degrees of freedom. The predicted response, $R_p(t)$, based on quiet-stance data closely predicts the actual dynamic response behavior, $R(t)$, for the subject presented in panel (a); here $\chi^2 = 59$. In panel (b), $R_p(t)$ poorly predicts $R(t)$ for the subject; here $\chi^2 = 652$.

(D_{js} and D_{jl}), scaling exponents (H_{js} and H_{jl}), and critical point coordinates, critical time interval (Δt_{jc}) and critical mean square displacement ($\langle \Delta j^2 \rangle_c$), where $j = x, y, r$. (Here we focus on AP stabilogram-diffusion parameters, where $j = y$.) Diffusion coefficients reflect the average level of stochastic activity of the postural control system. Scaling exponents, which range from 0 to 1, describe the likelihood of moving away from or toward a relative equilibrium point and quantify the correlation between increments of time, where $H = 0.5$ indicates an uncorrelated random walk process, $H > 0.5$ is associated with a persistence phenomenon such that current and future displacements of the COP are positively correlated, and $H < 0.5$ denotes anti-persistence such that displacements are negatively correlated. Critical time coordinates approximate the transition from short-term to long-term time interval regions.

We also calculated traditional sway parameters that are more commonly reported measures of COP time series data (e.g., Fernie et al., 1982; Overstall et al., 1977; Prieto et al., 1996). For each COP time series, we computed the maximum displacement, standard deviation,⁴ and the range between the maximum and minimum fluctuations of the AP COP about the origin ($\max(y)$, $\text{SD}(y)$, and $\text{range}(y)$, respectively).

For each subject, the average value of each parameter was computed for the 10 quiet-stance trials. Unpaired t -tests were used to examine whether these measures of postural stability varied by test group. To account for multiple comparisons, p -values below 0.006 were considered significant, while those between 0.006 and 0.05 were considered “borderline” significant.

3. Results

The actual and predicted dynamic response functions, $R(t)$ and $R_p(t)$, respectively, were significantly well-matched for eight of the 10 elderly subjects (χ^2 mean \pm SD: 192 ± 110 ; range: 59–368) and all 10 young adult subjects (χ^2 mean \pm SD: 198 ± 104 ; range: 45–308). The fit was poor for only two of the 10 elderly subjects (i.e., $\chi^2 \geq 652$). Thus, in the majority of cases, we were able to predict the behavior of the perturbation response from quiet-stance data.

Fig. 4 displays results for $R(t)$ and $R_p(t)$ for two elderly subjects. All subjects exhibited the expected curve shape for both functions, i.e., both panels display curves that decay from 1.0 and then fluctuate around an equilibrium state. The goodness-of-fit can be visually evaluated with respect to: the rate of decay, the magnitude of the equilibrium state, and the time at which equilibrium was attained. χ^2 decreases as the similarities between the two curves increase. Fig. 4a illustrates an example of an excellent fit, i.e., $\chi^2 = 59$. Note how the curves match each other quite well. Alternatively, Fig. 4b illustrates a poor fit, where $\chi^2 = 652$. Note that the rates of decay and times to equilibrium for each panel are different.

Statistically significant differences in supplemental balance measures were found between the young and elderly groups (Table 1). In general, elderly subjects had significantly larger ($p < 0.006$) AP fluctuations of the COP, e.g., mean (\pm SD) of the maximum AP displacement for elderly and young adults were 13.8 ± 3.4 mm and 8.8 ± 1.5 mm, respectively. There were also significant differences in the stabilogram-diffusion analysis parameters. For example, short-term AP diffusion coefficients for elderly adults were larger, which implies that elderly adults have greater short-term postural sway in the AP direction than young adults.

⁴The standard deviation of our adjusted zero-mean data is equivalent to the root mean square (RMS) of these data, for large n , i.e., $\text{SD}(y) = [\sum(y(i))^2/(n-1)]^{1/2}$, $\text{RMS}(y) = [\sum(y(i))^2/n]^{1/2}$, and $n = 3600$.

Table 1

Mean anterior–posterior balance parameters (\pm one standard deviation) based on quiet-standing data using traditional sway and stabilogram-diffusion analysis techniques

Parameter	Young (<i>N</i> = 10)	Elderly (<i>N</i> = 10)	<i>p</i>
<i>Traditional sway</i>			
SD(<i>y</i>)	3.2 \pm 0.6	4.5 \pm 0.8	0.001*
Max(<i>y</i>)	8.8 \pm 1.5	13.8 \pm 3.4	0.0005*
Range(<i>y</i>)	15.8 \pm 2.8	23.6 \pm 4.7	0.0003*
<i>Stabilogram-diffusion analysis</i>			
<i>D</i> _{ys}	4.5 \pm 1.8	13.4 \pm 5.2	0.0001*
<i>D</i> _{yl}	1.0 \pm 0.5	1.0 \pm 0.9	0.9
<i>H</i> _{ys}	0.62 \pm 0.07	0.74 \pm 0.06	0.0004*
<i>H</i> _{yl}	0.28 \pm 0.07	0.13 \pm 0.07	0.0001*
Δt_{yc}	1.3 \pm 0.4	1.3 \pm 0.6	0.9
$\langle \Delta y^2 \rangle_c$	9.8 \pm 5.4	27.0 \pm 13.9	0.002*

**p* < 0.006 based on unpaired *t*-test.

All traditional sway parameters have units of mm, unless noted. Short-term (*D*_{ys}) and long-term (*D*_{yl}) diffusion coefficients have units of mm²/s. Short-term (*H*_{ys}) and long-term (*H*_{yl}) scaling exponents are dimensionless. Critical time intervals (Δt_{yc}) have units of s. Critical mean square displacements ($\langle \Delta y^2 \rangle_c$) have units of mm².

We were unable to identify specific differences in demographic, clinical, or balance characteristics between elderly subjects who did, or did not, show a good fit between the actual and predicted dynamic response functions.

4. Discussion

Our results suggest that, by applying a linear relationship derived from the fluctuation–dissipation theorem (FDT), it is possible to predict the dynamic response of the postural control system after a mild perturbation using only quiet-standing COP data in both healthy young and elderly adults. We hypothesized that this FDT-based linear relationship would not hold for older adults since alterations occur in postural control with age. Our data from the supplemental balance measures indicated that there were significant differences in quiet-stance postural sway and stability between the young and elderly groups. However, we found that the FDT-based technique was applicable to eight of 10 elderly test subjects, as well as all of the young subjects. This novel finding suggests that the postural control system may use the same control mechanisms during quiet-stance and mild-perturbation conditions, regardless of age or quiet-stance behavior. This stems from the FDT-based conclusion that when the postural control system is not in equilibrium, it cannot distinguish whether it was brought into that state by an intrinsic, random fluctuation or a mild, external perturbation.

These findings may have promising clinical implications. They suggest that it may not be necessary to perform tests that involve *mild* perturbations to assess postural control capacity in healthy adults. Further studies are necessary to determine whether this technique is applicable to individuals with impairments in balance that may place them at a greater risk for falls, and to tests using larger perturbations. If it can be shown that this FDT-based technique is applicable to such conditions and individuals, then perturbation tests may be deemed unnecessary. Physically perturbing a fragile individual to evaluate balance control increases the potential for falls during tests. Therefore, the development of a simple, non-stressful technique to analyze postural control is highly desirable. Consequently, testing procedures that use only quiet-stance data to predict dynamic response behavior to any amount of perturbation would be beneficial for ensuring the safety of the individuals being tested.

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