

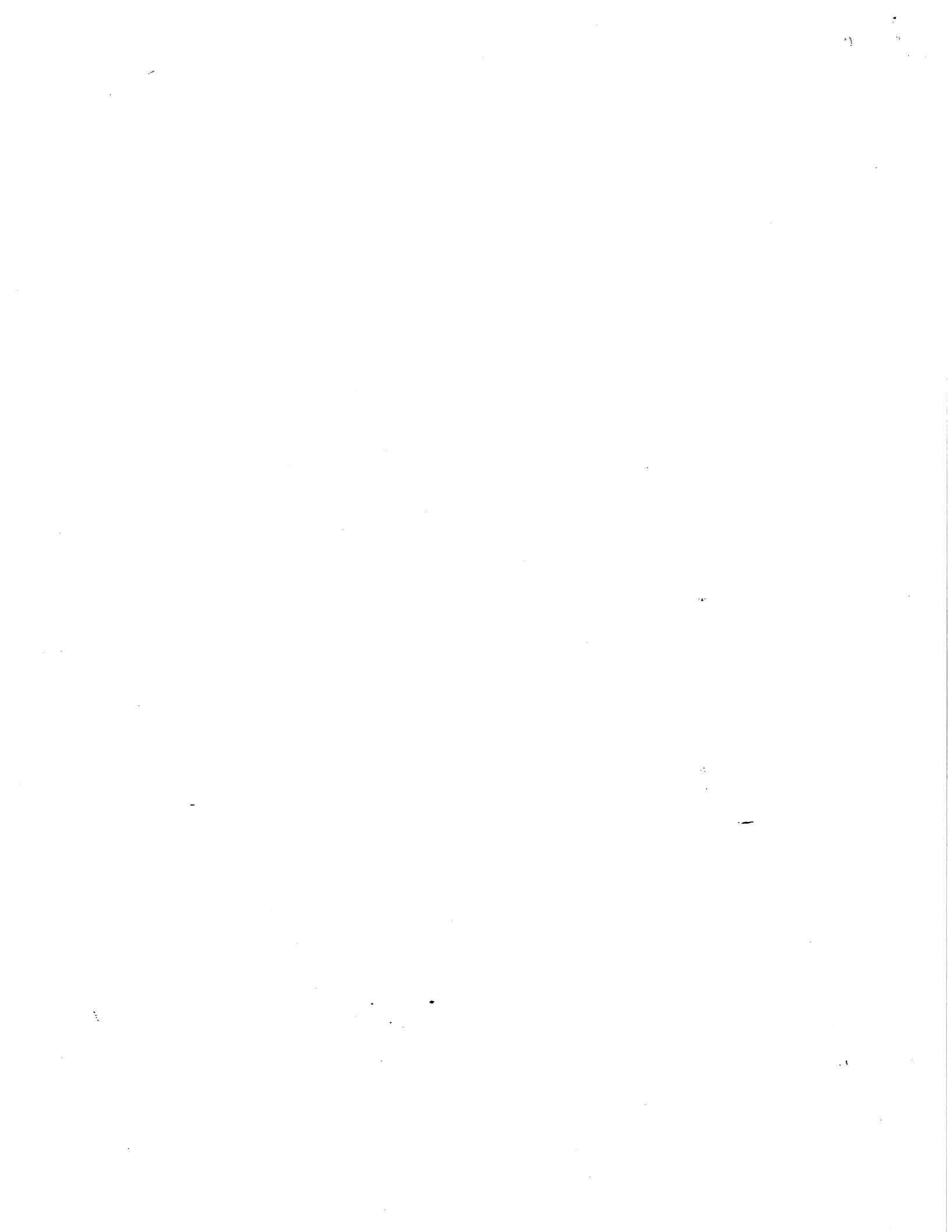
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## **Age-related changes in open-loop and closed-loop postural control mechanisms**

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**Abstract** In an earlier posturographic investigation (Collins and De Luca 1993) it was proposed that open-loop and closed-loop control mechanisms are involved in the regulation of undisturbed, upright stance. In this study, stabilogram-diffusion analysis was used to examine how the natural aging process affects the operational characteristics of these control mechanisms. Stabilogram-diffusion analysis leads to the extraction of repeatable center-of-pressure (COP) parameters that can be directly related to the steady-state behavior and functional interaction of the neuromuscular mechanisms underlying the maintenance of erect posture. Twenty-five healthy young males (aged 19–30 years) and twenty-five elderly males (aged 71–80 years) who were free of major gait and postural disorders were included in the study. An instrumented force platform was used to measure the time-varying displacements of the COP under each subject's feet during quiet standing. The COP trajectories were analyzed as one-dimensional and two-dimensional random walks, according to stabilogram-diffusion analysis. Using this technique, it was demonstrated cross-sectionally that healthy aging is associated with significant changes in the 'quasi-static' dynamics of the postural control system. (It was also shown that more traditional posturographic analyses, i.e., summary statistics, were not sensitive enough to detect these age-related differences.) It was found that the steady-state behavior of the open-loop postural control mechanisms in the elderly is more positively correlated and therefore perhaps more

unstable, i.e., the output of the overall system has a greater tendency to move or drift away from a relative equilibrium point over the short term. In contrast with this result, it was also found that the steady-state behavior of the closed-loop postural control mechanisms in the elderly is more negatively correlated and therefore perhaps more stable, i.e., over the longer term, there is an increased probability that movements away from a relative equilibrium point will be offset by corrective adjustments back towards the equilibrium position. In addition, it was demonstrated that the elderly utilize open-loop control schemes for longer time intervals and correspondingly larger COP displacements during periods of undisturbed stance. This result suggests that in the elderly there is a greater delay, on average, before closed-loop feedback mechanisms are called into play. Finally, it was shown that there is an increased heterogeneity of postural control abilities in healthy older adults.

**Key words** Balance · Elderly · Center of pressure · Random walk · Human

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## Introduction

A number of neuromuscular modifications accompany the normal aging process. Advancing age has been associated, for example, with muscle weakness (Faulkner et al. 1990), reduced cutaneous sensation (Whanger and Wang 1974), diminished proprioception (Skinner et al. 1984), and decreased nerve conduction velocity (Dorfman and Bosley 1979). These degenerative changes can impair balance control in many different ways (Horak et al. 1989; Lord et al. 1991; Prieto et al. 1993; Alexander 1994). Accordingly, the elderly are often predisposed to falls (Tinetti et al. 1988; Tinetti and Speechley 1989; Lipsitz et al. 1991), which are a common cause of morbidity and mortality among older persons. Despite the severity and frequency of this problem, postural instability in the elderly remains a poorly understood phenomenon.

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A number of recent studies have documented age-related changes in the strategies that are utilized by the postural control system to correct for various external perturbations and disturbances (Woollacott et al. 1986; Maki et al. 1987; Manchester et al. 1989; Stelmach et al. 1989; Alexander et al. 1992). Little is known, however, as to how the 'quasi-static' performance and characteristics of the postural control system are affected by the aforementioned age-dependent alterations to sensory and muscular subsystems. This situation is complicated by the fact that the results of previous studies analyzing quiet-standing postural stability among individuals of different age groups have been ambiguous – some have reported age-related differences in postural sway (Sheldon 1963; Hasselkus and Shambes 1975; Overstall et al. 1977; Era and Heikkinen 1985; Ring et al. 1989; Pyykkö et al. 1990; Hytönen et al. 1993), whereas others have found none (Dornan et al. 1978; Fernie et al. 1982). For instance, Overstall et al. (1977) reported that total anteroposterior (AP) sway increased with age; however, Fernie et al. (1982) found that a related measure – mean speed of sway – did not exhibit an age-related trend. In addition, the motor control insights gained from the majority of these earlier studies have been meager, largely because the analyses of the posturographic data have been limited to summary statistics, which, in general, cannot be interpreted in a physiologically meaningful way. For instance, it is unclear how the aforementioned summary measures (i.e., total AP sway and mean speed of sway) can be related to the operational characteristics of the neuromuscular mechanisms involved in balance control. Thus, given this paucity of physiologically relevant information and given that static posturography (compared with dynamic posturography) is a much simpler and safer test to perform and administer to elderly individuals, there is a clear need to gain an increased understanding of the effects of age on the regulation of undisturbed stance.

In an earlier study (Collins and De Luca 1993), we examined quiet-standing center-of-pressure (COP) trajectories as one-dimensional and two-dimensional random walks. This work was based on the assumption that the movements of the COP represent the combined output of co-existent deterministic and stochastic mechanisms. These analyses revealed that over short-term intervals of time<sup>1</sup> during undisturbed stance the COP behaves as a positively correlated random walk, i.e., one which tends to move or drift away from a relative equilibrium point following a perturbation, whereas over long-term intervals of time it resembles a negatively correlated random walk, i.e., one which tends to return to a relative equilibrium point following a perturbation. 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 intervals, respectively (an open-loop control

<sup>1</sup> It is important to note that the concept of time in stabilogram-diffusion analysis corresponds to a moving time window as opposed to the passage of real time

system is one which operates without feedback, whereas a closed-loop control system is one which operates with feedback). From this perspective, our approach, known as *stabilogram-diffusion analysis*, has the advantage that it leads to the extraction of repeatable COP parameters which can be directly related to the steady-state behavior and functional interaction of the neuromuscular mechanisms underlying the maintenance of upright stance.

In the present study, we utilized stabilogram-diffusion analysis and the open-loop/closed-loop postural control hypothesis to examine how the natural aging process affects the operational characteristics of the control mechanisms that are involved in the regulation of quiet standing.

## Methods

### Experimental methods

Included in the study were 25 healthy young males (age: 19–30 years, mean 22 years) and 25 elderly males (age: 71–80 years, mean 75 years). The subjects in the two populations were of similar size – body weight (mean±standard deviation): 70.7±8.4 kg (young), 77.4±9.5 kg (elderly); and height: 173.8±5.9 cm (young), 171.9±6.4 cm (elderly). Individuals were excluded from the investigation if they had a known history or evidence of a gait or postural disorder, or if they had lost their balance and fallen within the last five years. Informed consent was obtained from each subject prior to participation. This study was approved by the Boston University Charles River Campus Institutional Review Board.

Postural sway was evaluated by using a Kistler 9287 multi-component force platform to measure the time-varying displacements of the COP under a subject's feet. The force platform data were sampled at a frequency of 100 Hz [the noise characteristics of the platform are described by Collins and De Luca (1993)]. Each subject was instructed to stand upright on the platform in a standardized stance; the subjects' feet were abducted 10° and their heels were separated mediolaterally by a distance of 6 cm. During the testing, the subjects stood barefoot with their arms relaxed comfortably at their sides and their eyes fixed on a point in front of them. A series of 10 trials was conducted for each subject. Each trial lasted for a period of 30 s. Rest periods of 60 s were provided between each trial.

### Clinical evaluation and subject classification

As suggested by Alexander (1994), it is possible that some of the previously reported age-related differences in postural control may have been due to subtle, undetected disease in the elderly subjects, i.e., the clinical screening procedures and inclusion criteria of these earlier studies may not have been sufficiently strict. In order to minimize the possible effects of disease-related functional declines on the present posturographic analyses, a physician trained in geriatric medicine (A.B.) performed a complete medical evaluation of the 25 elderly subjects who passed the initial screening criteria described above. Specific attention was paid to clinical findings associated with impaired balance and gait. The evaluation included a complete history and review of medications, with attention to medical conditions and drugs associated with increased risk of falls; a physical examination, including evaluation of postural vital signs, cardiovascular function, neurologic findings, and vision; and an assessment of cognitive function and mood with standardized instruments (Folstein et al. 1975; Yesavage and Sheikh 1986).

An independent panel of geriatric specialists with expertise in falls established a priori criteria for increased risk of impaired bal-

**Table 1** Clinical reasons for exclusion of 13 elderly subjects from the sub-population of healthy elderly

Subject	Reasons(s) for exclusion
1	Macular degeneration, cataracts, flurazepam medication
2	Visual impairment
3	Orthostatic hypotension, cervical and knee arthritis
4	Vertigo
5	Diabetes mellitus
6	Cervical arthritis, tremor
7	Vertigo, transient ischemic attacks
8	Diabetes mellitus, vertigo, impaired vibratory sensation
9	Vertigo, doxepin medication
10	Diabetes mellitus
11	Orthostatic hypotension, tremor
12	Macular degeneration, orthostatic tachycardia
13	Myocardial infarction, pacemaker, chemotherapy for lymphoma, neck and knee arthritis

ance. These criteria included: (1) medical conditions such as visual problems, chronic arthritis, and cardiovascular problems; (2) medications such as psychotropics and blood pressure-lowering drugs; and (3) physical examination findings such as neurologic abnormalities, orthostatic hypotension, and joint deformities. Subjects who met criteria for potential balance impairment were designated as 'at risk for falls'. The other subjects were classified as 'healthy'. Thirteen of the 25 elderly subjects included in the study were classified as 'at risk for falls'. Table 1 lists the clinical reasons as to why each of these individuals were so classified.

#### Stabilogram-diffusion analysis

The COP trajectories were studied as one-dimensional and two-dimensional random walks according to stabilogram-diffusion analysis (Collins and De Luca 1993). In stabilogram-diffusion analysis, the displacement analysis of COP trajectories is carried out by computing the square of the displacements between all pairs of points separated in time by a specified time interval  $\Delta t$  (Fig. 1a). The square displacements are then averaged over the number of  $\Delta t$  making up the COP time series. This process is repeated for increasing values of  $\Delta t$ . A plot of mean square COP displacement (e.g.,  $\langle \Delta r^2 \rangle$ ) versus  $\Delta t$  is known as a *stabilogram-diffusion plot*<sup>2</sup> (Fig. 1b). Stabilogram-diffusion plots are computed for each subject trial and then 10 such curves are averaged to obtain a resultant stabilogram-diffusion plot for a particular subject. A more complete description of stabilogram-diffusion analysis is given by Collins and De Luca (1993, 1995a).

A schematic representation of a typical resultant stabilogram-diffusion plot is shown in Fig. 1b. In order to parameterize such plots, two regions are identified – a short-term region and a long-term region (denoted by subscripts *s* and *l*, respectively, throughout the manuscript). These regions are separated by a transition or critical period over which the slope of the stabilogram-diffusion plot changes considerably. Stabilogram-diffusion analysis involves the extraction of three sets of posturographic parameters: diffusion coefficients, scaling exponents, and critical point coordinates.

Diffusion coefficients reflect the level of stochastic activity and/or energy of the COP along the mediolateral (ML) or AP axis or about the plane of support. From a physiological standpoint, the short-term and long-term COP diffusion coefficients characterize

the stochastic activity of the open-loop and closed-loop postural control mechanisms, respectively. Diffusion coefficients  $D_j$  are calculated from the slopes of the resultant linear-linear plots of mean square COP displacement versus  $\Delta t$ , according to the general expression

$$\langle \Delta j^2 \rangle = 2D_j \Delta t \quad (1)$$

where  $\langle \Delta j^2 \rangle$  is the mean square COP displacement, and  $j=x,y,r$ .

Scaling exponents, which can be any real number in the range  $0 < H_j < 1$ , quantify the correlation between the step increments making up an experimental time series. If  $H_j = 0.5$ , then the increments in displacement are statistically independent. This is the result expected for classical Brownian motion. If  $H_j > 0.5$ , then past and future increments are positively correlated (Feder 1988; Saupe 1988). In this case, a random walker moving in a particular direction for some  $t_0$  will tend to continue in the same direction for  $t > t_0$ . In general, an increasing (decreasing) trend in the past implies an increasing (decreasing) trend in the future. On the other hand, if  $H_j < 0.5$ , then the stochastic process is negatively correlated (Feder 1988; Saupe 1988). In this case, increasing (decreasing) trends in the past imply on the average decreasing (increasing) trends in the future. From a physiological standpoint, COP scaling exponents quantify the correlated behavior of the respective postural control mechanisms, i.e., short-term scaling exponents (which are typically greater than 0.5) characterize the drift-like dynamics of the open-loop postural control mechanisms, whereas long-term scaling exponents (which are typically less than 0.5) characterize the antidrift-like dynamics of the closed-loop postural control mechanisms. Scaling exponents  $H_j$  are calculated from the slopes of the resultant log-log plots of mean square COP displacement versus  $\Delta t$ , according to the generalized scaling law

$$\langle \Delta j^2 \rangle \sim \Delta t^{2H_j} \quad (2)$$

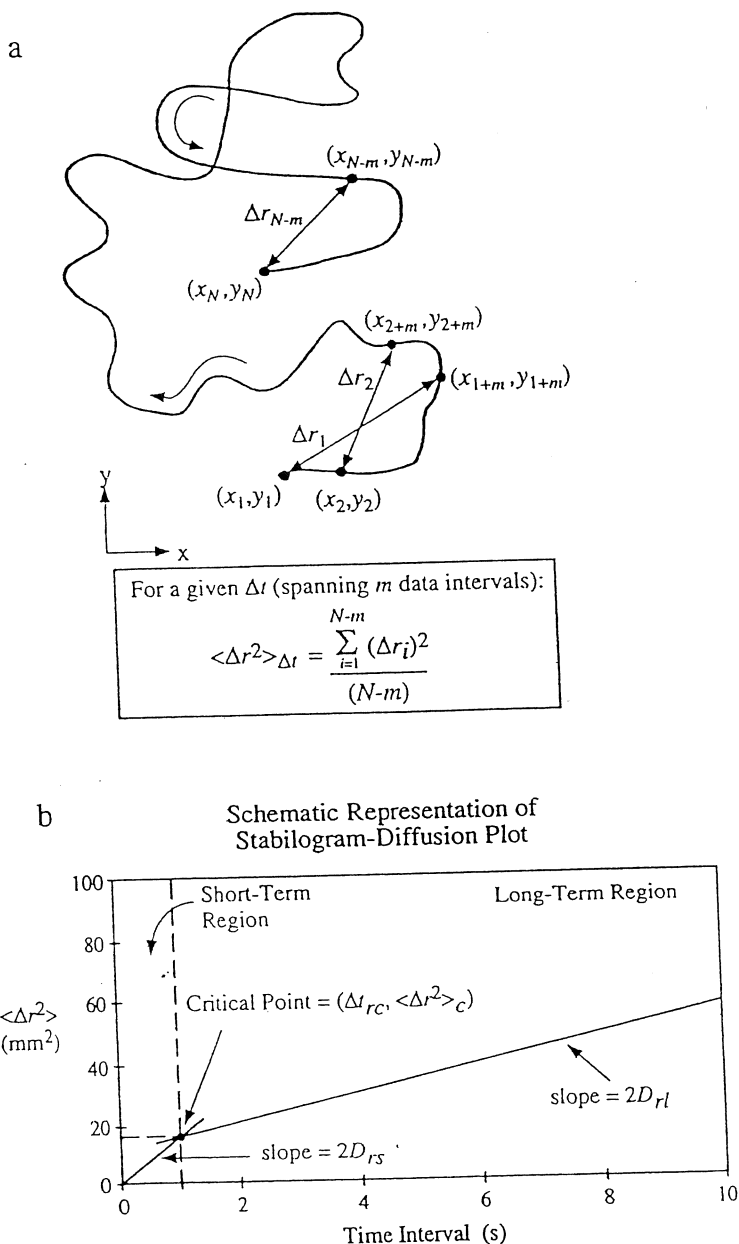
where the symbols correspond to those of Eq. 1. Diffusion coefficients and scaling exponents are each computed for both the short-term and long-term regions of resultant stabilogram-diffusion plots. In the present study, the respective slopes needed to calculate these parameters were determined by utilizing the method of least squares to fit straight lines through defined portions of the aforementioned plots. All parameters were determined by a single investigator.

The critical point coordinates – the critical time interval  $\Delta t_{jc}$  and critical mean square displacement  $\langle \Delta j^2 \rangle_c$ , where  $j=x,y,r$  – approximate the transition region that separates the short-term and long-term regions. An estimate for each critical point was determined as the intersection point of the straight lines fitted to the two regions of the linear-linear version of each resultant stabilogram-diffusion plot (Fig. 1b). From a physiological standpoint, these coordinates approximate the temporal and spatial characteristics of the region over which the postural control system switches from open-loop control to closed-loop control.

The above approach involves the fitting of two different models (when  $H_j \neq 0.5$ ) to the same data sets, i.e., diffusion coefficients representing the slope of a linear model (see Eq. 1), and scaling exponents representing the exponent of a scaling-law model (see Eq. 2). In a recent set of studies (Collins and De Luca 1994, 1995b), we demonstrated that COP trajectories are significantly different from uncorrelated random walks and that the aforementioned (short-range and longer-range) correlations in the COP time series are due to underlying dynamic processes. This result implies that the non-linear data-analysis technique is more valid than the linear data-analysis technique. Given this result, the COP diffusion coefficients, which are calculated using the linear data-analysis technique, should be viewed as 'effective' diffusion coefficients (such measures represent 'actual' diffusion coefficients only when  $H_j = 0.5$ , which is rarely the case with quiet-standing COP trajectories). As such, these parameters approximate the effective diffusion of the COP about the base of support. From this perspective and from the standpoint of our postural control hypothesis, the short-term and long-term effective diffusion coefficients should be interpreted as approximate measures of the effective stochasticity of the open-loop and closed-loop control mechanisms, respectively.

<sup>2</sup> In the present study,  $\{x_t\}$  and  $\{y_t\}$  are the ML and AP COP time series, respectively, and  $\langle \Delta r^2 \rangle = \langle \Delta x^2 \rangle + \langle \Delta y^2 \rangle$ . Thus, *r* designates planar COP measurements and displacements. The brackets  $\langle \rangle$  denote an average over time or an ensemble average over a large number of samples

**Fig. 1** a Diagram showing the method for calculating mean square planar displacement  $\langle \Delta r^2 \rangle$  as a function of time interval  $\Delta t$  for a COP trajectory made up of  $N$  data points  $(x_1, y_1; x_2, y_2; \dots; x_N, y_N)$ . Similar techniques are also used to calculate  $\langle \Delta x^2 \rangle$  and  $\langle \Delta y^2 \rangle$  as functions of  $\Delta t$ . In this case,  $\Delta t$  does not represent the sampling interval, instead  $\Delta t$  represents a moving time window spanning  $m$  data intervals. The summation for calculating mean square displacement for a given time interval is for  $(N-m)$  computed displacements. Thus, the last displacement which can be and is considered in the random-walk analysis is that between the  $(N-m)$ th point and the  $N$ th point of the time series. **b** A schematic representation of a typical resultant planar stabilogram-diffusion plot ( $\langle \Delta r^2 \rangle$  vs  $\Delta t$ ) generated from COP time series according to the method shown in **a**. The effective diffusion coefficients  $D_{rs}$  and  $D_{rl}$  are computed from the slopes of the lines fitted to the short-term and long-term regions, respectively. The critical point,  $(\Delta t_{rc}, \langle \Delta r^2 \rangle_c)$ , is defined by the intersection of the lines fitted to the two regions of the plot. The scaling exponents  $H_{rs}$  and  $H_{rl}$  are calculated from the slopes of the log-log plots of the short-term and long-term regions, respectively (from Collins and De Luca 1993)



### Traditional COP parameters

The following commonly used COP parameters were also calculated from the stabilogram time series: maximum AP displacement, maximum ML displacement, root-mean-square displacement, total sway path, and radial area (Hasan et al. 1990). The above parameters were computed for each subject trial and then the respective values were averaged for each set of 10 trials to obtain a resultant measure for each parameter for each subject.

### Statistical analyses

In the first set of statistical analyses, the  $F$  test and Student's  $t$ -test were used to compare the variances and group means, respectively, of the stabilogram-diffusion parameters and traditional COP parameters that were calculated for the young ( $N=25$ ) and elderly ( $N=25$ ) populations. If the young and elderly population variances for a particular parameter were sufficiently different, then a weighted analysis was used to estimate the standard error of the difference between the two means.

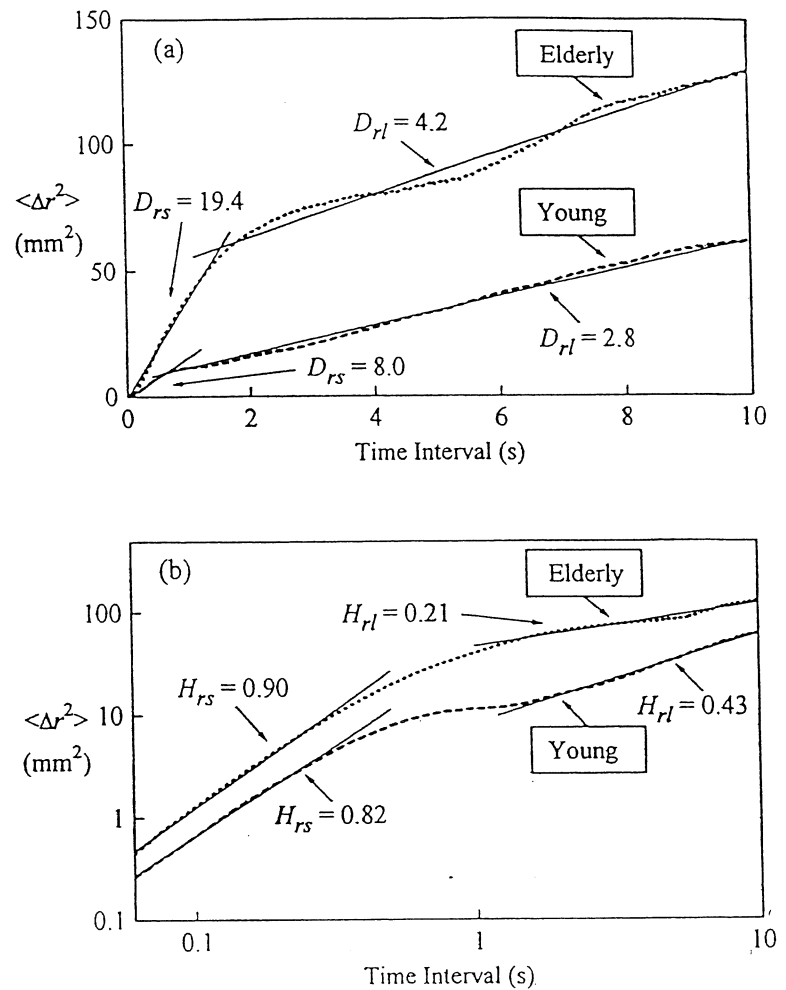
For the second set of statistical analyses, the population of elderly subjects was separated into two groups – healthy elderly ( $N=12$ ) and at-risk elderly ( $N=13$ ) – according to the classification scheme described earlier. (The parameterization of the posturographic data and the clinical evaluation/classification of the elderly subjects were double-blinded.) The Student-Newman-Keuls multiple range test was used to perform pairwise comparisons between the computed posturographic results for the young, healthy elderly, and at-risk elderly populations. The  $F$  test was also used to compare the variances of the respective parameters that were calculated for the three subject populations.

## Results

### Entire subject sample

We begin by comparing the posturographic results for the young subjects with those for the entire group of 25 elder-

Fig. 2a,b Raw-data resultant planar stabilogram-diffusion plots and fitted regression lines for one representative healthy young subject (age 20 years) and one representative healthy elderly subject (age 71 years): a linear-linear plots, b log-log plots. Values for the computed short-term and long-term effective diffusion coefficients (in units of  $\text{mm}^2 \text{s}^{-1}$ ) are given in a, where the computed critical point coordinates are:  $\Delta t_{rc} = 0.7 \text{ s}$  (young),  $1.5 \text{ s}$  (elderly), and  $\langle \Delta r^2 \rangle_c = 10.7 \text{ mm}^2$  (young),  $59.6 \text{ mm}^2$  (elderly). Values for the computed short-term and long-term scaling exponents are given in b. The lines fitted for computation of  $D_{rs}$ ,  $D_{rl}$ ,  $H_{rs}$ , and  $H_{rl}$  for the representative young subject had  $r^2$  values of 0.98, 1.00, 1.00, and 0.99, respectively, while for the representative elderly subject the respective  $r^2$  values were 0.99, 0.98, 1.00, and 0.93

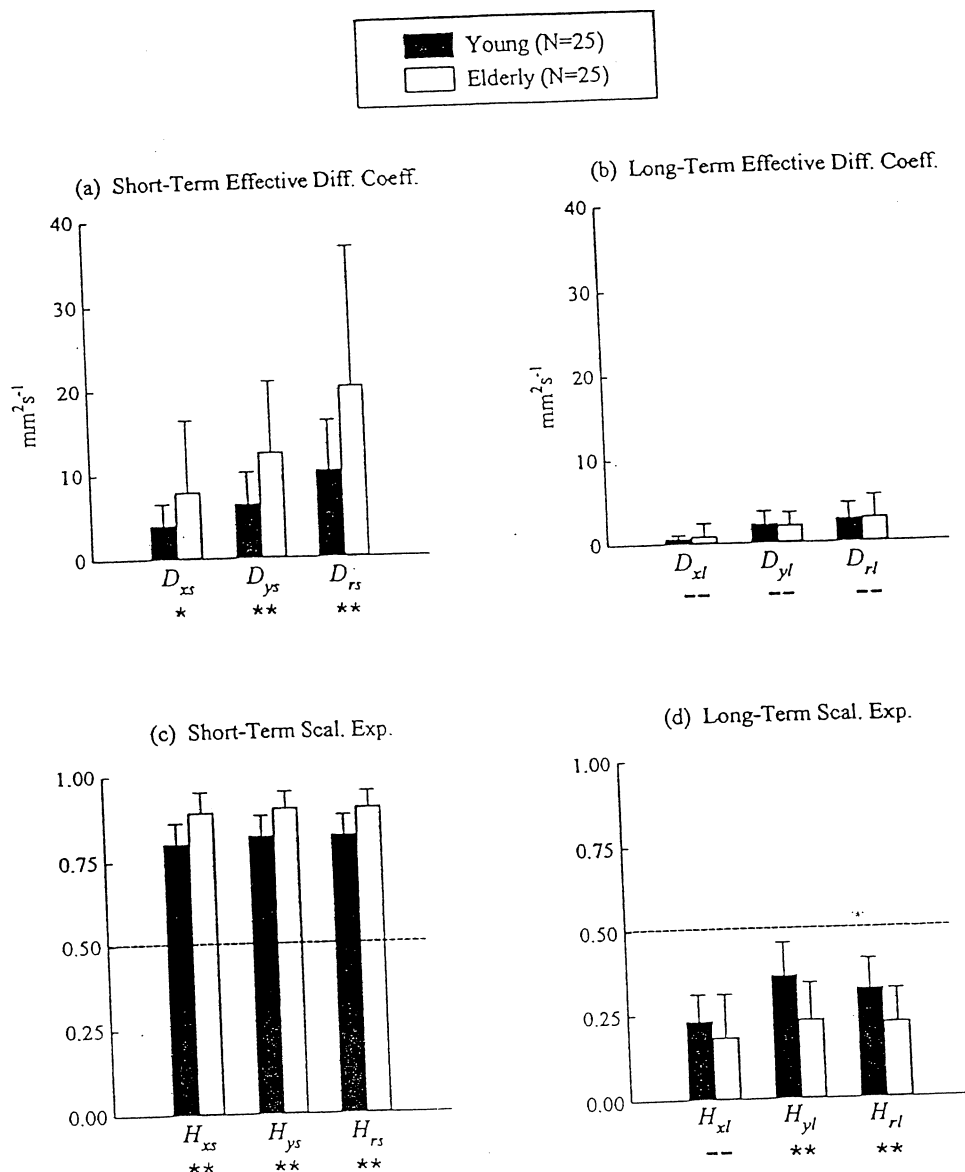


ly subjects. These aged subjects, who were free of major gait and postural disorders, were considered representative of typical elderly from the population at large. Raw-data resultant planar stabilogram-diffusion plots for representative young and elderly subjects are given in Fig. 2. Several comparative points about these plots should be noted. Firstly, from the linear-linear plots of mean square COP displacement versus time interval (Fig. 2a), it can be seen that the slope of the short-term region for the elderly subject was substantially larger than that for the young subject, whereas the slopes of the long-term region for the two subjects were relatively similar. These findings were reflected in the computed values for the effective diffusion coefficients – the short-term effective diffusion coefficient ( $D_{rs}$ ) for the aged subject was substantially greater than that for the young subject, whereas the long-term effective diffusion coefficients ( $D_{rl}$ ) for the two subjects were relatively similar (Fig. 2a). Secondly, it should be noted from Fig. 2a that the transition region between the short-term and long-term regions for the representative elderly subject occurred over larger mean square COP displacements and larger time intervals than that for the representative young subject. These differences were reflected in the calculated values for the critical point coordinates – the critical mean square displacement ( $\langle \Delta r^2 \rangle_c$ ) and critical time

interval ( $\Delta t_{rc}$ ) for the elderly subject were both larger than those for the young subject (see Fig. 2). Finally, from the log-log plots of mean square COP displacement versus time interval (Fig. 2b), it can be seen that the slopes of the short-term and long-term regions for the elderly subject were respectively greater and less than those for the young subject. These differences were reflected in the computed values for the scaling exponents – the elderly subject's short-term and long-term scaling exponents ( $H_{rs}$  and  $H_{rl}$ , respectively) were respectively larger and smaller than those for the young subject (Fig. 2b). As will be described below, these representative findings, in general, capture the significant differences between the two populations.

The group means and standard deviations of the calculated stabilogram-diffusion parameters for the young and elderly populations are given in bar-plot form in Figs. 3 and 4. Firstly, there were statistically significant differences between the elderly and young short-term effective diffusion coefficients (Fig. 3a) – the respective group means for the elderly subjects were approximately twice those for the young subjects. However, there were no significant differences between the elderly and young long-term effective diffusion coefficients (Fig. 3b). Secondly, the respective short-term scaling exponents for the elderly subjects were significantly greater ( $P < 0.005$ )

**Fig. 3a-d** Group means and standard deviations for the young ( $N=25$ ) and elderly ( $N=25$ ) subjects: **a** short-term effective diffusion coefficients, **b** long-term effective diffusion coefficients, **c** short-term scaling exponents, **d** long-term scaling exponents. Dashed line value expected for classical Brownian motion, i.e.,  $H_f=0.50$ . \*, \*\* Statistically significant differences at  $P<0.05$  and  $0.005$ , respectively; -- statistical comparisons that were not significant



than those for the young subjects (Fig. 3c). The COP trajectories for the elderly subjects were thus more positively correlated over short-term intervals of time. On the other hand, the AP and planar long-term scaling exponents for the elderly subjects were significantly smaller ( $P<0.005$ ) than those for the young subjects (Fig. 3d). Thus, over long-term intervals of time, the COP trajectories for the aged subjects were more negatively correlated in the AP direction (changes in planar stabilogram-diffusion parameters, e.g.,  $H_{rl}$ , are directly related to changes in the respective AP and/or ML parameters). Finally, for all three resultant plots (ML, AP, and planar), both the critical mean square displacements and critical time intervals for the elderly subjects were significantly greater than those for the young subjects (Fig. 4).

The group means and standard deviations of the traditional COP parameters for the young and elderly populations are shown in bar-plot form in Fig. 5. There were no significant differences between the two groups for the

majority of these parameters. Only one such parameter – maximum AP displacement – was significantly different ( $P<0.05$ ) between the two populations.

The results from the  $F$  tests are summarized in Table 2. Between the young and elderly subjects, there were statistically significant differences in the variance of 11 of the 18 stabilogram-diffusion parameters and in the variance of one (maximum ML displacement) of the five traditional COP parameters. The majority of these differences were significant at  $P<0.005$ . In each case, the variance for the elderly population was significantly greater than that for the young population.

#### Subgroup analysis

Since some of the increased variance in the elderly population may have been due to the presence of medical conditions and medications with subclinical effects on



Fig. 4a,b Group means and standard deviations for the young ( $N=25$ ) and elderly ( $N=25$ ) subjects: a critical time intervals, b critical mean square displacements. Symbols as in Fig. 3

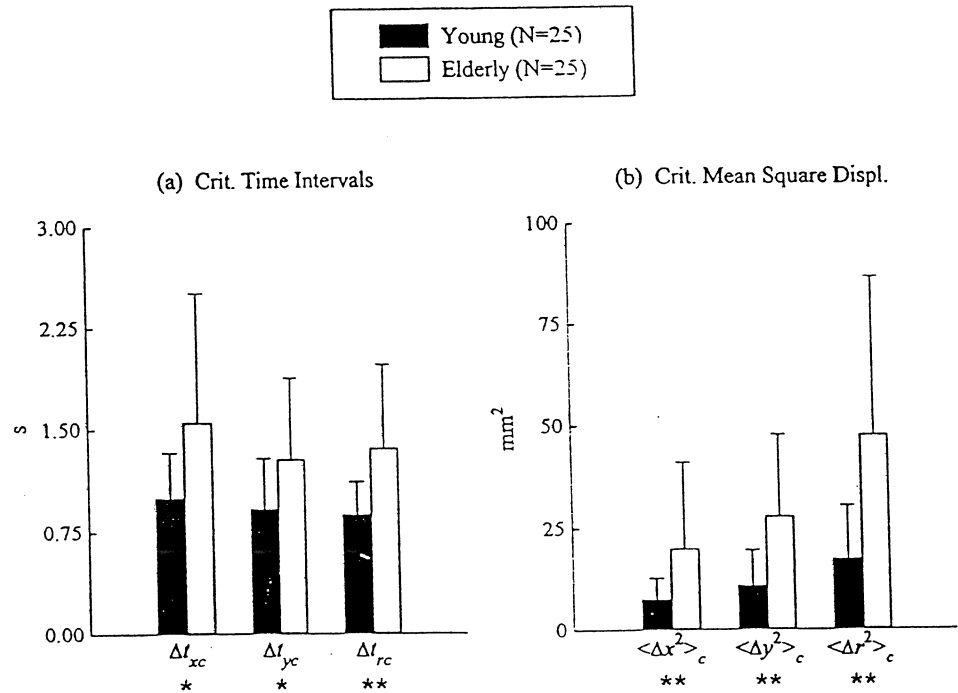
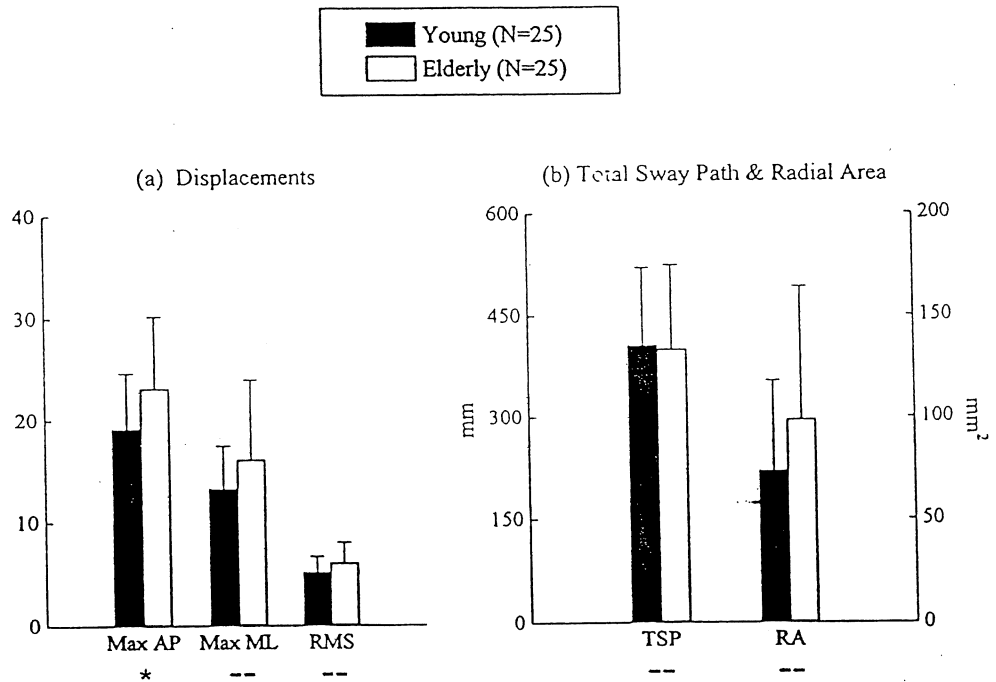


Fig. 5 Group means and standard deviations for the young ( $N=25$ ) and elderly ( $N=25$ ) subjects for the following traditional COP parameters: a maximum anteroposterior displacement ( $Max AP$ ), maximum mediolateral displacement ( $Max ML$ ), and root-mean-square displacement ( $RMS$ ); b total sway path ( $TSP$ ) and radial area ( $RA$ ). Symbols as in Fig. 3



balance control and since such factors may have also influenced the aforementioned young-elderly differences in quiet-standing dynamics, we separated the aged population into two groups – healthy elderly and at-risk elderly. Figure 6 presents the group means and standard deviations of the effective diffusion coefficients and scaling exponents for the young, healthy elderly, and at-risk elderly populations. The statistical results from the pairwise comparisons are summarized below each bar plot. There were no significant differences between the heal-

thy elderly and young subjects for any of the short-term effective diffusion coefficients (Fig. 6a). However, the at-risk elderly had a significantly larger short-term AP effective diffusion coefficient than both the young subjects and healthy elderly. The short-term planar effective diffusion coefficient for the at-risk elderly population was also significantly larger than that for the young population. From Fig. 6b, it can be seen that there were no significant differences between the respective populations for any of the long-term effective diffusion coefficients.

**Table 2** Results from the  $F$  tests comparing the variances of the respective COP parameters for the different subject populations. \*, \*\* Statistically significant differences at  $P < 0.05$  and  $0.005$ , respectively; -  $F$  tests that were not significant. *Max. AP displ.* maximum anteroposterior displacement, *Max. ML displ.* maximum mediolateral displacement, *RMS Displ.* root-mean-square displacement, *Y* young, *Et* elderly (total), *Eh* elderly (healthy), *Er* elderly (at risk)

Parameter	Y-Et	Y-Eh	Y-Er	Eh-Er
$D_{xx}$	**	**	**	-
$D_{yy}$	**	**	**	-
$D_{rs}$	**	**	**	-
$D_{xt}$	**	-	**	**
$D_{yt}$	-	-	-	-
$D_{rl}$	-	-	*	-
$H_{xx}$	-	-	-	-
$H_{yy}$	-	-	-	-
$H_{rs}$	-	-	-	-
$H_{xt}$	*	-	*	-
$H_{yt}$	-	-	-	-
$H_{rl}$	-	-	-	-
$\Delta t_{xc}$	**	**	**	-
$\Delta t_{yc}$	*	-	**	*
$\Delta t_{rc}$	**	-	**	*
$\langle \Delta x^2 \rangle_c$	**	**	**	-
$\langle \Delta y^2 \rangle_c$	**	**	**	-
$\langle \Delta r^2 \rangle_c$	**	**	**	-
Max. AP displ.	-	-	-	-
Max. ML displ.	**	*	*	-
RMS displ.	-	-	-	-
Total sway path	-	-	-	-
Radial area	-	-	-	-

All pairwise comparisons of the short-term scaling exponents, with the exception of  $H_{xs}$  for the healthy elderly and at-risk elderly, indicated significant differences between the subject populations (Fig. 6c). In each of these cases, the short-term scaling exponent for the at-risk elderly was significantly greater than that for the healthy elderly which was significantly greater than that for the young subjects. In addition, the long-term AP and planar scaling exponents for both the healthy elderly and at-risk elderly were significantly smaller than the respective measures for the young subjects (Fig. 6d). These differences are clearly illustrated in the scatter plots of Fig. 7. The young subjects typically exhibited relatively small short-term scaling exponents and relatively large long-term scaling exponents, whereas the opposite situation generally held for the elderly subjects, with the at-risk elderly typically exhibiting larger short-term scaling exponents than the healthy elderly.

Figure 8 presents the group means, standard deviations, and a results summary of the pairwise comparisons of the critical point coordinates for the three subject populations. There were no significant differences between the respective groups for either  $\Delta t_{xc}$  or  $\Delta t_{yc}$  (Fig. 8a). However, the planar critical time interval for both the healthy elderly and at-risk elderly was significantly greater than that for the young subjects. In addition, the AP and planar critical mean square displacements for both the healthy elderly and at-risk elderly were signifi-

cantly larger than the respective measures for the young subjects (Fig. 8b).

The results for the traditional COP parameters for the young, healthy elderly and at-risk elderly populations are presented and summarized in Fig. 9. There were no statistically significant differences between the respective populations for any of the traditional parameters.

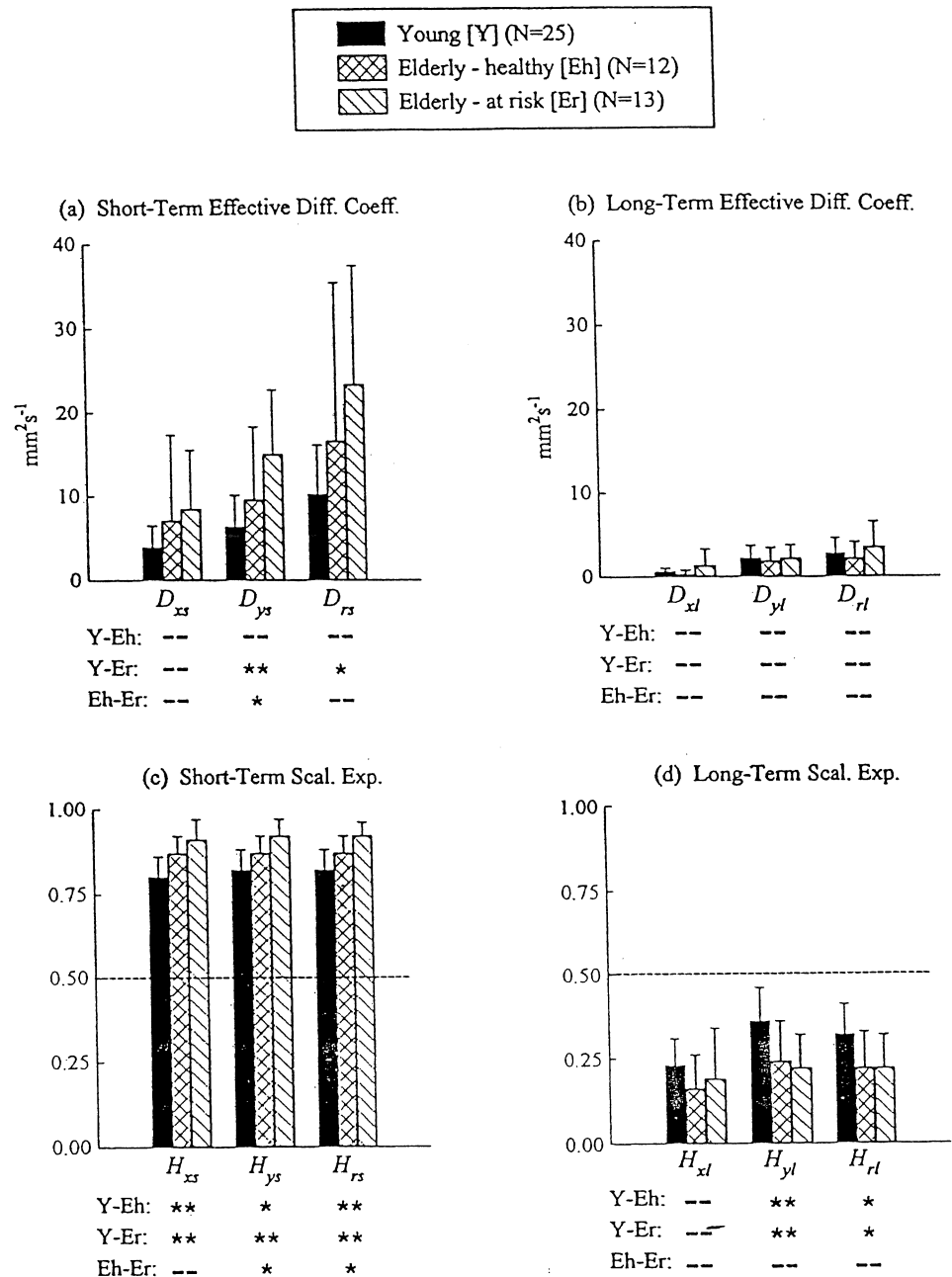
The results from the  $F$  tests comparing the variances of the respective COP parameters for the three subject populations are summarized in Table 2. There were significant differences between the healthy elderly and young subjects in the variance of seven of the 18 stabilogram-diffusion parameters and in the variance of one (maximum ML displacement) of the five traditional COP parameters. Between the at-risk elderly and young subjects, there were significant differences in the variance of 12 of the 18 stabilogram-diffusion parameters and also in the variance of maximum ML displacement. In each of the above cases, the variance for the elderly population was significantly greater than that for the young population. There were also significant differences between the healthy elderly and at-risk elderly in the variance of three stabilogram-diffusion parameters -  $D_{xt}$ ,  $\Delta t_{yc}$ , and  $\Delta t_{rc}$ . In each case, the variance for the at-risk elderly was significantly greater than that for the healthy elderly.

## Discussion

In the present study, we demonstrated cross-sectionally that healthy aging is associated with significant changes in the 'quasi-static' dynamics of the postural control system and that these changes can be quantified during undisturbed stance using stabilogram-diffusion analysis. We also showed that more traditional posturographic analyses, i.e., summary statistics, were not sensitive enough to detect these age-related differences. These results were derived from a comparison of healthy young subjects with a population of carefully screened, healthy elderly subjects. The young-elderly differences in quiet-standing dynamics are likely to be due to age-dependent alterations in the steady-state behavior and functional interaction of the underlying neuromuscular control mechanisms. Accordingly, below we interpret the present posturographic findings from the standpoint of our open-loop/closed-loop postural control hypothesis.

The short-term ML and AP scaling exponents for the healthy elderly were significantly larger than those for the young subjects (as noted above, changes in planar stabilogram-diffusion parameters, e.g.,  $H_{rs}$ , are directly related to changes in the respective ML and/or AP parameters). This result suggests that the steady-state behavior of the open-loop postural control mechanisms in the elderly is more positively correlated and therefore, perhaps more unstable, i.e., the output of the overall system has a greater tendency to move or drift away from a relative equilibrium point over the short term.

Fig. 6 Group means and standard deviations for the young ( $N=25$ ), healthy elderly ( $N=12$ ), and at-risk elderly ( $N=13$ ) subjects: **a** short-term effective diffusion coefficients, **b** long-term effective diffusion coefficients, **c** short-term scaling exponents, **d** long-term scaling exponents. *Dashed line* value expected for classical Brownian motion, i.e.,  $H_f=0.50$ . The *table* below each plot summarizes the statistical results from the pairwise comparisons of the respective populations. Symbols as in Fig. 3



This change may be due, in part, to a postural control strategy<sup>3</sup> adopted by elderly individuals whereby they increase the net stiffness of their musculoskeletal system by increasing the level of muscular activity across the joints of their lower limbs.<sup>4</sup> A potential advantage of

<sup>3</sup> We recognize that there are other plausible strategies and/or functional changes which could account for these posturographic results. We present this hypothesized, age-dependent postural control strategy as only one possibility

<sup>4</sup> Since the stiffness of an activated muscle (i.e., its resistance to stretch) is directly related to the tensile force developed in that muscle, the co-activation of antagonistic muscles can be used to modulate the net mechanical stiffness of a joint (i.e., its resistance to movement), without changing the resultant moment acting about the joint (Winters et al. 1988)

this strategy is that 'stiffer' systems are better at resisting and correcting for transient perturbations. This strategy could be disadvantageous, however, given that 'stiffer' active muscles exhibit a higher level of stochastic activity. More specifically, since fluctuations are always present in the mechanical output of skeletal muscles (De Luca et al. 1982) and since the average amplitude of these noise-like fluctuations increases as the amount of force produced by a muscle increases (Joyce and Rack 1974), the aforementioned postural control strategy would lead to increased short-term fluctuations across the joints. In an unstable system (such as an inverted pendulum or upright biped), these alterations would, in general, lead to an increased tendency to

Fig. 7 Scatter-plots of a short-term and long-term AP scaling exponents and b short-term and long-term planar scaling exponents during quiet standing. Each subject is represented once in each of the two plots

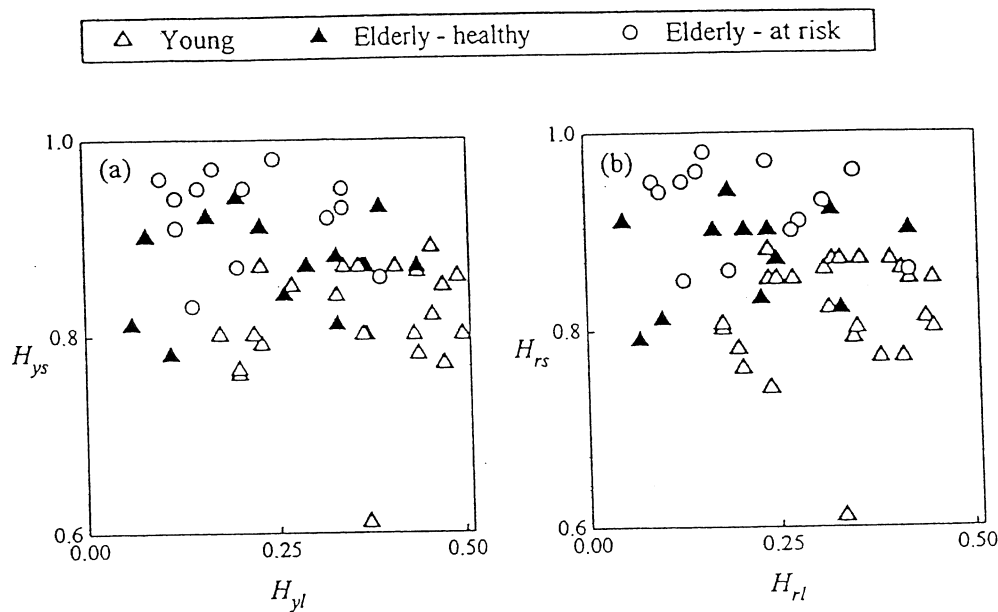
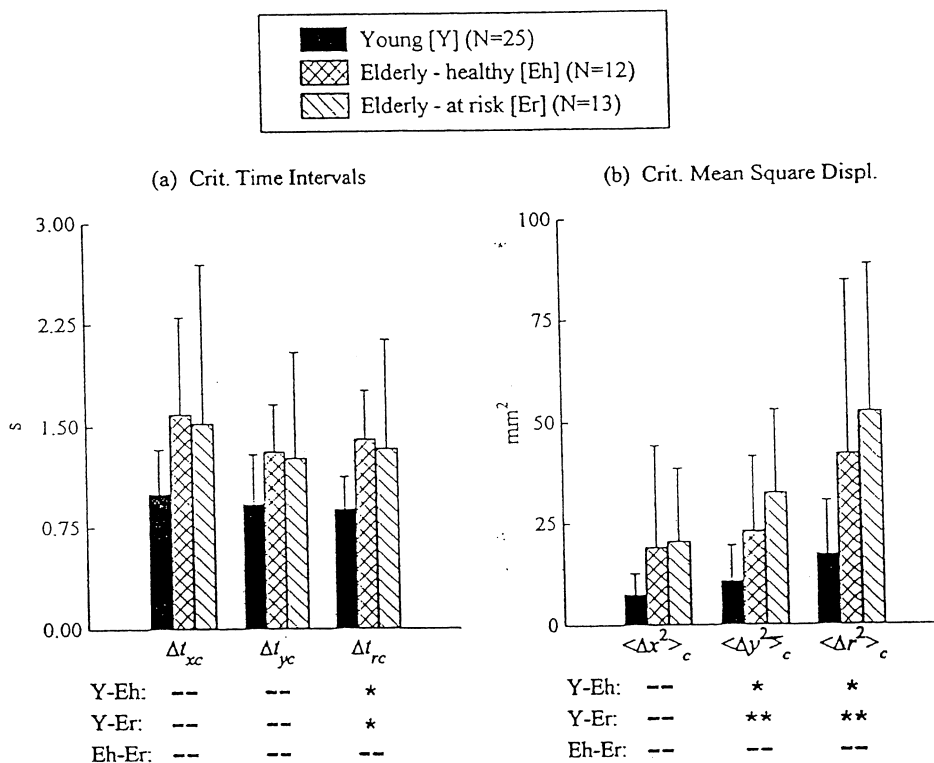


Fig. 8 Group means and standard deviations for the young (N=25), healthy elderly (N=12), and at-risk elderly (N=13) subjects: a critical time intervals, b critical mean square displacements. The table below each plot summarizes the statistical results from the pairwise comparisons of the respective populations. Symbols as in Fig. 3



drift<sup>5</sup> in some direction for short-term intervals of time and thus result in larger short-term scaling exponents, as were calculated for the healthy elderly.<sup>6</sup> These changes occurred in both the x- and y-directions implying that the muscles involved act mediolaterally and anteroposteriorly.

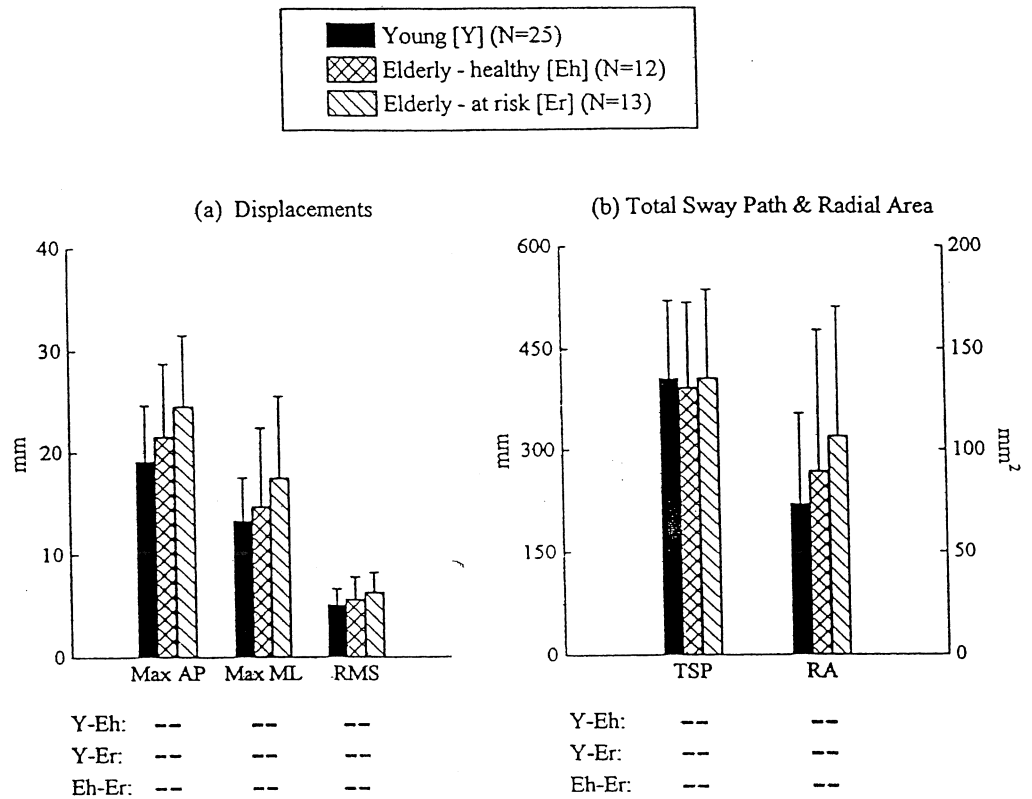
It is also expected that this postural control strategy would lead to higher average levels of short-term postur-

al sway and therefore result in larger short-term effective diffusion coefficients. Although the respective mean values for  $D_{xs}$  and  $D_{ys}$  for the healthy elderly were larger than those for the young subjects, these differences were

<sup>5</sup> Winters et al. (1988) have shown that musculoskeletal models which utilize antagonist co-activation for open-loop quasi-static position control exhibit position drift

<sup>6</sup> With sensitive, i.e., extremely low-noise, surface EMG electrodes, it should be possible to test this hypothesized postural control strategy. However, this was not considered as part of the study at the outset; it will be a part of future work. Although the relationship between recorded EMG signals and resultant joint stiffness has not been well established, it is expected that the EMG RMS value for a particular muscle will increase if the muscle's level of activity (and hence its stiffness) is increased.

**Fig. 9a,b** Group means and standard deviations for the young ( $N=25$ ), healthy elderly ( $N=12$ ), and at-risk elderly ( $N=13$ ) subjects for the following traditional COP parameters: **a** maximum anteroposterior displacement (*Max AP*), maximum mediolateral displacement (*Max ML*), and root-mean-square displacement (*RMS*); **b** total sway path (*TSP*) and radial area (*RA*). The table below each plot summarizes the statistical results from the pairwise comparisons of the respective populations. Symbol -- as in Fig. 3



not significant ( $P=0.15$  and  $0.13$ , respectively). The predicted co-parameter change, however, was borne out and is clearly illustrated by the computed results for the at-risk elderly, who had significantly larger mean values for  $H_{yx}$  and  $D_{yx}$  than both the young subjects and healthy elderly. In the case of the healthy elderly, the increase in their short-term scaling exponents, and the proposed corresponding increase in muscular activity across their lower-limb joints, may not have caused a large enough increase in their short-term effective diffusion coefficients, as compared with the young subjects, to be detectable with the relatively small sample ( $N=12$ ) in our subgroup analysis.

This hypothesized, age-dependent postural control strategy is indirectly supported by previous dynamic posturographic investigations. Manchester et al. (1989), for example, showed that older adults utilize increased levels of antagonistic muscle activity during perturbation experiments. Consistent with the results of the present study, these authors also found that this effect was more pronounced in aged subjects with subtle, underlying pathology.

In contrast with the above short-term scaling-exponent results, we found that the long-term AP scaling exponent for the healthy elderly was significantly *smaller* than that for the young subjects. This finding suggests that the steady-state behavior of the closed-loop postural control mechanisms in the elderly is more negatively correlated and therefore perhaps more stable, i.e., over the longer term, there is an increased probability that movements away from a relative equilibrium point will

be offset by corrective adjustments back towards the equilibrium position. Such a change in control dynamics could be effected by an increase in the gain of the feedback mechanisms that are involved in the regulation of upright stance. A postural control strategy of this sort may allow elderly individuals to compensate for the aforementioned alterations in the steady-state behavior of the open-loop control mechanisms, i.e., to offset the effects of an increased tendency for short-term drift. These changes in the long-term dynamics of the postural control system could account for the finding that the long-term effective diffusion coefficients for the healthy elderly were smaller, albeit not significantly smaller, than those for the young subjects, i.e., an increase in gain, for a given level of effective stochastic activity, would decrease the probability of the COP moving a greater distance away from a relative equilibrium point and/or shifting between different equilibrium points, and thereby lead to lower long-term effective diffusion coefficients. The differences between the young and elderly long-term effective diffusion coefficients may not have been significant because the proposed gain changes would also have had to offset the indirect effects of the aged subjects' increased tendency for short-term drift, i.e., it is expected that an increase in short-term drift and/or fluctuations across the multiple joints of the body would lead to an increase in the long-term fluctuations of the overall system. Similar results were obtained with the at-risk elderly.

The healthy elderly were also characterized by significantly larger planar critical time intervals (the changes in

$\Delta t_{xc}$  and  $\Delta t_{yc}$  were not statistically significant, however, their combined effect on  $\Delta t_{rc}$  did produce a significant difference). This finding suggests that aged subjects utilize open-loop control mechanisms for longer intervals of time, and that in the elderly there is a greater delay, on average, before closed-loop feedback mechanisms are called into play. Such an alteration in postural control dynamics could lead to a more unstable situation during erect stance. This age-related modification in the temporal interaction of the open-loop and closed-loop control mechanisms may be due to a number of different factors. For example, it may be due in part to increased postural muscle response and reflex times, which have been documented as concomitants of the aging process (Inglin and Woollacott 1988; Stelmach et al. 1989, 1990). In addition, this change may be the result of diminished proprioception, which has also been reported as a common consequence of aging (Skinner et al. 1984). An individual with reduced proprioception or joint position sense may not be able to detect small changes in body position during quiet standing. The body and/or individual body segments of such an individual may thus be allowed to drift over larger displacements and for correspondingly longer time intervals before corrective feedback mechanisms are utilized.

Likewise, it should be noted that the significant increase in the AP critical mean square displacement for the elderly subjects can be directly attributed to the combined effect of the increase in  $D_{ys}$  and the increase in  $\Delta t_{yc}$ , i.e., greater short-term effective stochastic activity utilized over longer time intervals would naturally lead to larger values for the critical mean square displacement. As with the aforementioned scalar changes in critical time interval, the changes in  $D_{ys}$  and  $\Delta t_{yc}$ , respectively, were not statistically significant, however, their combined effects on  $\langle \Delta y^2 \rangle_c$  did produce a significant difference. From a physiological standpoint, the significant increase in  $\langle \Delta y^2 \rangle_c$  in elderly subjects may be related to age-dependent increases in proprioceptive thresholds, in accordance with the arguments presented above.

We also demonstrated that there is an increased heterogeneity of postural control abilities in healthy older adults. The variance of seven of the 18 stabilogram-diffusion parameters (and one of the five traditional COP parameters) for the healthy elderly was significantly greater than the variance of the respective measures for the young subjects. Given that the healthy elderly were carefully screened for subtle pathology, these differences in population variability cannot be attributed to underlying disease; instead, these differences were likely due to physiologic aging. Importantly, we also found that the number of stabilogram-diffusion parameters indicating significant young-elderly differences in variance and/or group mean was reduced substantially with the separation of the aged population into two groups – subjects 'at risk for falls' and 'healthy' subjects. This latter result confirms the need for using careful screening procedures and strict inclusion criteria in future posturographic studies of older persons.

On a final note, it is intriguing to consider the possibility of using short-term stabilogram-diffusion parameters as clinical measures of postural instability. Both  $D_{ys}$  and  $H_{ys}$  indicated significant differences between the healthy elderly and at-risk elderly that were not evident from summary COP measures, such as total sway path or radial area. The consistent changes in the aforementioned dynamic COP measures for the present heterogeneous population of at-risk elderly (i.e., subjects with a myriad of medical conditions and risk factors) may have been due to a common compensatory postural control strategy, e.g., one that involved the stiffening of the musculoskeletal system via increased muscular activity, as opposed to a common disease-related change in the underlying control mechanisms. Likewise, the at-risk elderly may have behaved similarly due to a general 'fear of falling' (Maki et al. 1991) or a lack of confidence in their ability to maintain balance during quiet standing. Further work with well-defined patient populations is needed.

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## References

- Alexander NB (1994) Postural control in older adults. *J Am Geriatr Soc* 42:93–108
- Alexander NB, Shepard N, Gu MJ, Schultz A (1992) Postural control in young and elderly adults when stance is perturbed: kinematics. *J Gerontol* 47:M79–87
- Collins JJ, De Luca CJ (1993) Open-loop and closed-loop control of posture: a random-walk analysis of center-of-pressure trajectories. *Exp Brain Res* 95:308–318
- Collins JJ, De Luca CJ (1994) Random walking during quiet standing. *Phys Rev Lett* 73:764–767
- Collins JJ, De Luca CJ (1995a) The effects of visual input on open-loop and closed-loop postural control mechanisms. *Exp Brain Res* 103:151–163
- Collins JJ, De Luca CJ (1995b) Upright, correlated random walks: a statistical-biomechanics approach to the human postural control system. *CHAOS* 5:57–63
- De Luca CJ, LeFever RS, McCue MP, Xenakis AP (1982) Control scheme governing concurrently active human motor units during voluntary contractions. *J Physiol (Lond)* 329:129–142
- Dorfman LJ, Bosley TM (1979) Age-related changes in peripheral and central nerve conduction in man. *Neurology* 29:38–44
- Dorman J, Fernie GR, Holliday PJ (1978) Visual input: its importance in the control of postural sway. *Arch Phys Med Rehab* 59:586–591
- Era P, Heikkinen E (1985) Postural sway during standing and unexpected disturbance of balance in random samples of men of different age groups. *J Gerontol* 40:287–295
- Faulkner JA, Brooks SV, Zerba E (1990) Skeletal muscle weakness and fatigue in old age: underlying mechanisms. *Annu Rev Gerontol Geriatr* 10:147–166
- Feder J (1988) *Fractals*. Plenum Press, New York
- Fernie GR, Gryfe CI, Holliday PJ, Llewellyn A (1982) The relationship of postural sway in standing to the incidence of falls in geriatric subjects. *Age Ageing* 11:11–16
- Folstein MF, Folstein S, McHugh PR (1975) Mini-mental state. *J Psychiatr Res* 12:189–196

- Hasan SS, Lichtenstein MJ, Shiavi RG (1990) Effects of loss of balance on biomechanics platform measures of sway: influence of stance and a method for adjustment. *J Biomech* 23:783-789
- Hasselkus BR, Shambes GM (1975) Aging and postural sway in women. *J Gerontol* 30:661-667
- Horak FB, Shupert CL, Mirka A (1989) Components of postural dyscontrol in the elderly: a review. *Neurobiol Aging* 10:727-738
- Hytönen M, Pyykkö I, Aalto H, Starck J (1993) Postural control and age. *Acta Otolaryngol (Stockh)* 113:119-122
- Inglin B, Woollacott M (1988) Age-related changes in anticipatory postural adjustments associated with arm movements. *J Gerontol* 43:M105-113
- Joyce GC, Rack PMH (1974) The effects of load and force on tremor at the normal human elbow joint. *J Physiol (Lond)* 240:375-396
- Lipsitz LA, Jonsson PV, Kelley MM, Koestner JS (1991) Causes and correlates of recurrent falls in ambulatory frail elderly. *J Gerontol* 46:M114-122
- Lord SR, Clark RD, Webster IW (1991) Postural stability and associated physiological factors in a population of aged persons. *J Gerontol* 46:M69-76
- Maki BE, Holliday PJ, Fernie GR (1987) A posture control model and balance test for the prediction of relative postural stability. *IEEE Trans Biomed Eng* 34:797-810
- Maki BE, Holliday PJ, Topper AK (1991) Fear of falling and postural performance in the elderly. *J Gerontol* 46:M123-131
- Manchester D, Woollacott M, Zederbauer-Hylton N, Marin O (1989) Visual, vestibular and somatosensory contributions to balance control in the older adult. *J Gerontol* 44:M118-127
- Overstall PW, Exton-Smith AN, Imms FJ, Johnson AL (1977) Falls in the elderly related to postural imbalance. *Br Med J* 1:261-264
- Prieto TE, Myklebust JB, Myklebust BM (1993) Characterization and modeling of postural steadiness in the elderly: a review. *IEEE Trans Rehab Eng* 1:26-34
- Pyykkö I, Jäntti P, Aalto H (1990) Postural control in elderly subjects. *Age Ageing* 19:215-221
- Ring C, Nayak USL, Isaacs B (1989) The effect of visual deprivation and proprioceptive change on postural sway in healthy adults. *J Am Geriatr Soc* 37:745-749
- Saupe D (1988) Algorithms for random fractals. In: Peitgen H-O, Saupe D (eds) *The science of fractal images*. Springer, New York Berlin Heidelberg, pp 71-136
- Sheldon JH (1963) The effect of age on the control of sway. *Gerontol Clin* 5:129-138
- Skinner HB, Barrack RL, Cook SD (1984) Age-related decline in proprioception. *Clin Orthop* 184:208-211
- Stelmach GE, Phillips J, DiFabio RP, Teasdale N (1989) Age, functional postural reflexes, and voluntary sway. *J Gerontol* 44:B100-106
- Stelmach GE, Populin L, Müller F (1990) Postural muscle onset and voluntary movement in the elderly. *Neurosci Lett* 117:188-193
- Tinetti ME, Speechley M (1989) Prevention of falls among the elderly. *N Engl J Med* 320:1055-1059
- Tinetti ME, Speechley M, Ginter SF (1988) Risk factors for falls among elderly persons living in the community. *N Engl J Med* 319:1701-1707
- Whanger AD, Wang HS (1974) Clinical correlates of the vibratory sense in elderly psychiatric patients. *J Gerontol* 29:39-45
- Winters J, Stark L, Seif-Naraghi A-H (1988) An analysis of the sources of musculoskeletal system impedance. *J Biomech* 21:1011-1025
- Woollacott MH, Shumway-Cook A, Nashner LM (1986) Aging and postural control: changes in sensory organization and muscular organization. *Int J Aging Hum Dev* 23:97-114
- Yesavage JA, Sheikh JI (1986) Geriatric depression scale. *Clin Gerontol* 5:165-172