Measures of Postural Steadiness: Differences Between Healthy Young and Elderly Adults

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***Abstract*— Measures of postural steadiness are used to characterize the dynamics of the postural control system associated with maintaining balance during quiet standing. The objective of this study was to evaluate the relative sensitivity of center-of-pressure (COP)-based measures to changes in postural steadiness related to age. A variety of time and frequency domain measures of postural steadiness were compared between a group of twenty healthy young adults (21–35 years) and a group of twenty healthy elderly adults (66–70 years) under both eyes-open and eyes-closed conditions. The measures that identified differences between the eyes-open and eyes-closed conditions in the young adult group were different than those that identified differences between the eye conditions in the elderly adult group. Mean velocity of the COP was the only measure that identified age-related changes in both eye conditions, and differences between eye conditions in both age groups. The results of this study will be useful to researchers and clinicians using COP-based measures to evaluate postural steadiness.**

I. Introduction

POSTURAL steadiness is the dynamics of the postural control system associated with maintaining balance during quiet standing. The control of posture is maintained by a complex sensorimotor system, which integrates information from the visual, vestibular, and somatosensory systems [14]. Postural dyscontrol in the elderly may reflect subclinical pathologies affecting one or more components of the postural control system, as well as age-related changes in the sensorimotor systems [12]. Characterizing age-related changes in postural steadiness will advance our understanding of the ways in which the postural control system is compromised with the aging process, and may provide information useful in identifying elderly persons at risk of falling [12], [39].

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The integrity of the postural control system is typically evaluated with tests of static and/or dynamic posturography [14], [32]. Dynamic posturography characterizes the performance of the postural control system by measuring the postural response to an applied or volitional postural perturbation. Postural steadiness, or static posturography, characterizes the performance of the postural control system in a static position and environment during quiet standing. Postural steadiness evaluations often include both eyes-open and eyes-closed trials to estimate the role of the visual system in maintaining standing balance. The ratio of the eyes-closed measure to the eyes-open measure is referred to as the Romberg ratio [46].

Postural steadiness is most often characterized with measures based on the displacement of the center-of-pressure (COP) measured with a force platform, the horizontal and vertical reaction forces also measured with a force platform, or the horizontal displacement at the subject's waist with a Wright ataxiameter. The COP is the location of the vertical reaction vector on the surface of a force platform on which the subject stands [49]. The COP reflects the orientations of the body segments (joint angles), as well as the movements of the body (joint angular velocities and accelerations) to keep the center-of-gravity over the base-of-support. The anterior-posterior (AP) and medial-lateral (ML) displacement of the COP can be measured with a force platform. The planar trajectory of the COP over the test interval is commonly referred to as a stabilogram. The Wright ataxiameter [29] consists of a box which sits on the floor behind the subject, from which a wand extends vertically to approximately the height of the waist. The upper end of the wand is attached by a string to the subject's waist. Total angular displacement in the AP direction is measured. An evaluation of the correlation between the displacement of the COP measured with a Kistler force platform and the angular displacement at the hip measured with a Wright ataxiameter has been reported [28].

Although force platforms have been used to evaluate postural steadiness for at least two decades [15], [26], [42], COP-based measures of postural steadiness have only been collectively discussed and evaluated by Hufschmidt *et al.* [13], in a comparison of normals and patients with cerebellar and labyrinthine lesions to test the diagnostic significance of a group of measures. The subject groups were compared with mean velocity, mean distance, mean frequency, and sway area measures, as well as the corresponding Romberg ratios, and AP and ML directional component measures.

Age-related changes in postural steadiness have been identified with a variety of methods and measures. The relative sensitivity of COP-based measures to age-related changes in postural steadiness is difficult to ascertain from the literature because of the diversity of methodologies used. Previous studies have been conducted with a force plate [5], [9], [10], [18], [20], [25], [26], Wright ataxiameter [2], [29], or other devices [4], [38]. Prior to the availability of analog-to-digital (A/D) converters, measures of postural steadiness were typically based on manual measurements of strip chart recordings of force or displacement signals [26], [43]. Most of these studies evaluated the subjects in a comfortable self-chosen stance [2], [5], [20], [25], [26], [29], [38], but some constrained the orientation and separation of the feet [9], [10], [18]. Some studies characterized postural steadiness under eyes-open conditions only [9], [10], [20], [26], [29]; others conducted both eyes-open and eyes-closed trials [2], [4], [5], [18], [25], [38]. Some studies scaled the measures to the area [9], [10] or length [20] of the base of support. Most of these studies characterized postural steadiness with measures related to the velocity of the measured displacement [2], [4], [5], [18], [20], [25], [26], [29], the area of the stabilogram [9], [10], [25], [38], or the mean displacement of the COP [20], [26]. Although most of these studies were based on a single measure, some included multiple measures [20], [25], [26]. For example, Maki *et al.* [20] computed root mean square (rms) distance, range, mean velocity, mean frequency, centroidal frequency, and frequency dispersion.

The purpose of this study was to collectively define and discuss COP-based measures of postural steadiness, and then evaluate the relative sensitivity of these measures to age-related changes in postural steadiness. Since COP-based measures of postural steadiness are designed to characterize a wide range of aspects of the stabilogram, it is anticipated that the relative sensitivity of these measures to age-related changes in postural steadiness may also vary considerably. A variety of measures were computed and used to compare postural steadiness in a group of healthy young adults to a group of healthy elderly adults, under both eyes-open and eyes-closed conditions. This summary and evaluation of COP-based measures of postural steadiness will be useful to researchers and clinicians who are using these measures to evaluate changes with age or neurologic disease, the effects of rehabilitation interventions or pharmacologic treatments, or the risk of falling in the elderly.

Although postural steadiness has been characterized with measures based on the magnitude and variation of the horizontal and/or vertical reaction forces [7], [24], [41], this evaluation focused exclusively on measures derived from the COP. In 1981, the International Society of Posturography suggested the use of two COP-based measures, mean velocity, and rms distance, in their recommendations for standardizing force platform based evaluations of postural steadiness [15]. The present study evaluated these and a variety of other postural steadiness measures. This study also evaluated relatively new measures for characterizing postural steadiness, such as fractal dimension, 95% confidence circle area, 50% power frequency, and 95% power frequency [27], [30]. These measures were included for their anticipated ability to estimate the area or dimensionality of the stabilogram, or the distribution of the power spectral density of the associated time series. It was not the intent to describe and evaluate all previously used COP-based measures, but rather to compare a representative set of these.

II. Methods

A. Subject Testing and Data Acquisition

The relative sensitivity of COP-based measures to age-related changes in postural steadiness was investigated with a group of 20 healthy young adults (ten male, ten female; mean age $\pm$ s.d.: 26.4 $\pm$ 4.9 years; range: 21 to 35 years) and a group of 20 healthy elderly adults (12 male, eight female; mean age $\pm$ s.d.: 68.0 $\pm$ 1.3 years; range: 66 to 70 years). Based on a self-report and a physical examination by a physician, none of the subjects had an orthopedic or neurologic disease, had consumed alcohol, or used medications that would compromise tests of postural performance. A neurologic exam was conducted on the healthy elderly subjects, who were independent community dwellers. All subjects provided written informed consent to participate in this research protocol, which has been approved by the Human Studies Subcommittee at the VA Medical Center and the IRB at the Medical College of Wisconsin.

For the eyes-open trial, each subject was asked to stand quietly in a comfortable stance near the center of a Kistler 9281A11 force platform, with arms at the side, and look straight ahead at a visual reference. A Metrabyte DAS-8 12-bit A/D converter, installed in an IBM-PC/AT compatible computer, was programmed to sample the eight Kistler 5001 charge amplifiers at 100 Hz for 30 s. After the eyes-open trial, the subject sat in a chair for approximately two minutes before the procedure was repeated with eyes closed.

B. Computation of COP-Based Measures

The COP is a bivariate distribution, jointly defined by AP and ML coordinates. The AP_O and ML_O time series define the COP path relative to the origin of the force platform coordinate system. These time series were computed using the digitized output signals of the force platform amplifiers [13]. LabVIEW 2 (National Instruments Corp., Austin, TX) was used to compute the COP time series and the measures of postural steadiness. After the measures were computed, the Romberg ratio, which is the eyes-closed measure divided by the corresponding eyes-open measure, was also computed.

The AP_O and ML_O time series were passed through a fourth-order zero phase Butterworth low-pass digital filter with a 5-Hz cut-off frequency. The last 20 s (2000 points) of the 30-s test period was used to compute the time and frequency domain measures. The mean COP is the position on the force platform defined by the arithmetic means of the AP_O and ML_O time series. In the following equations, all summations are from 1 to N, unless indicated otherwise; N, the number of data points included in the analysis, is 2000; and T, the period of time selected for analysis, is 20 s.

$$\overline{\mathrm{AP}} = 1/N \sum \mathrm{AP}_O[n], \quad \overline{\mathrm{ML}} = 1/N \sum \mathrm{ML}_O[n]. \tag{1}$$

To simplify the following definitions, the AP and ML time series are referenced to the mean COP.

$$\mathrm{AP}[n] = \mathrm{AP}_O[n] - \overline{\mathrm{AP}} \quad \mathrm{ML}[n] = \mathrm{ML}_O[n] - \overline{\mathrm{ML}}. \tag{2}$$

The COP coordinate time series, AP and ML, are commonly used to compute measures of postural steadiness, and characterize the static performance of the postural control system. In the strict sense, these axes are referenced to the force platform, not the subject. To evaluate the postural control system in a natural state, the subjects are allowed to stand in a comfortable self-chosen stance, facing toward the positive AP direction of the force platform. Since the orientation of the base-of-support is only approximately aligned with the axes of the force platform, measures based on the AP time series probably reflect some ML movements of the subject, and vice versa. Postural steadiness measures are also computed with another time series, which is derived from the COP but is not sensitive to the orientation of the base-of-support with respect to the force platform. The resultant distance (RD) time series is the vector distance from the mean COP to each pair of points in the AP_O and ML_O time series.

$$\mathrm{RD}[n] = \left[\mathrm{AP}[n]^2 + \mathrm{ML}[n]^2\right]^{1/2} \quad n = 1, \cdots, N. \tag{3}$$

The following equations are for the composite measures computed using both the AP and ML time series, and those based on the AP time series. Every measure defined for the AP time series, is similarly defined for the ML time series. In these equations, it is assumed that the number of COP data points is large enough so that $N \approx N - 1$.

1) Time-Domain "Distance" Measures: The measures described in this section are the most commonly used measures of postural steadiness. Time-domain distance measures estimate a parameter associated with either the displacement of the COP from the central point of the stabilogram, or the velocity of the COP. The mean distance (MDIST) is the mean of the RD time series, and represents the average distance from the mean COP

$$\mathrm{MDIST} = 1/N \sum \mathrm{RD}[n]. \tag{4}$$

The mean distance-AP ($\mathrm{MDIST_{AP}}$) is the mean absolute value of the AP time series and represents the average AP distance from the mean COP

$$\mathrm{MDIST_{AP}} = 1/N \sum |\mathrm{AP}[n]|. \tag{5}$$

The rms distance (RDIST) from the mean COP is the RMS value of the RD time series

$$\mathrm{RDIST} = \left[1/N \sum \mathrm{RD}[n]^2\right]^{1/2}. \tag{6}$$

The rms distance-AP ($\mathrm{RDIST_{AP}}$) from the mean COP is the standard deviation of the AP time series

$$\mathrm{RDIST_{AP}} = s_{\mathrm{AP}} = \left[1/N \sum \mathrm{AP}[n]^2\right]^{1/2}. \tag{7}$$

The total excursions (TOTEX) is the total length of the COP path, and is approximated by the sum of the distances between consecutive points on the COP path

$$\begin{aligned}\mathrm{TOTEX} = \sum_{n=1}^{N-1} [(\mathrm{AP}[n+1] - \mathrm{AP}[n])^2 \\ + (\mathrm{ML}[n+1] - \mathrm{ML}[n])^2]^{1/2}.\end{aligned} \tag{8}$$

The total excursions-AP ($\mathrm{TOTEX_{AP}}$) is the total length of the COP path in the AP direction, and is approximated by the sum of the distances between consecutive points in the AP time series

$$\mathrm{TOTEX_{AP}} = \sum_{n=1}^{N-1} |\mathrm{AP}[n+1] - \mathrm{AP}[n]|. \tag{9}$$

The mean velocity (MVELO) is the average velocity of the COP. In effect, this normalizes the total excursions to the analysis interval. The COP time series are filtered to the frequency range of interest to minimize the quantization noise that may inadvertently inflate measures such as mean velocity and total excursions [8]

$$\mathrm{MVELO} = \mathrm{TOTEX}/T. \tag{10}$$

The mean velocity-AP ($\mathrm{MVELO_{AP}}$) is the average velocity of the COP in the AP direction

$$\mathrm{MVELO_{AP}} = \mathrm{TOTEX_{AP}}/T. \tag{11}$$

The range is the maximum distance between any two points on the COP path. The range-AP is the absolute value of the difference between the smallest and largest values in the AP time series.

2) Time-Domain "Area" Measures: A variety of methods have been used to estimate the area of the stabilogram [9], [10], [38]. The following measures were selected because they are relatively easy to compute, and are statistically based estimates of the area enclosed by the stabilogram. The 95% confidence circle area (AREA-CC) is the area of a circle with a radius equal to the one-sided 95% confidence limit of the RD time series. This models the area of the stabilogram with a circle that includes approximately 95% of the distances from the mean COP, assuming that the distances are normally distributed

$$\mathrm{AREA-CC} = \pi(\mathrm{MDIST} + z_{0.5} s_{\mathrm{RD}})^2. \tag{12}$$

where $z_{.05}$, the z statistic at the 95% confidence level, is 1.645 [37], and s_{RD} is the standard deviation of the RD time series

$$\begin{aligned} s_{\mathrm{RD}} &= \left[1/N \sum \mathrm{RD}^2[n] - \mathrm{MDIST}^2\right]^{1/2} \\ &= [\,\mathrm{RDIST}^2 - \mathrm{MDIST}^2]^{1/2}. \end{aligned} \tag{13}$$

The 95% confidence ellipse area (AREA-CE) is the area of the 95% bivariate confidence ellipse, which is expected to enclose approximately 95% of the points on the COP path. This is conceptually similar to the regression ellipse area [35], but is based on a different statistical model [33], [36]. The procedure for calculating a 95% confidence ellipse has been described in conjunction with a discussion of principal axes and confidence regions [40]. Following this derivation and assuming the sample size (n) is large enough so that $(n-1)/(n-2) \approx 1$, the major a and minor b radii of the 95%

confidence ellipse are

$$a = \left[\mathrm{F}_{.05[2,n-2]}\left(s_{AP}^2 + s_{\mathrm{ML}}^2 + \mathrm{D}\right)\right]^{1/2} \tag{14}$$

$$b = \left[\mathrm{F}_{.05[2,n-2]}\left(s_{AP}^2 + s_{\mathrm{ML}}^2 - D\right)\right]^{1/2} \tag{15}$$

where $F_{.05[2,\,n-2]}$ is the F statistic at a 95% confidence level for a bivariate distribution with n data points. For a large sample size (n >120), $\mathrm{F}_{.05[2,\infty]}$ is 3.00 [37]. s_{AP} and s_{ML} are the standard deviations of the AP and ML time series, respectively, and

$$\mathrm{D} = \left[\left(s_{AP}^2 + s_{\mathrm{ML}}^2\right) - 4\left(s_{\mathrm{AP}}^2 s_{\mathrm{ML}}^2 - s_{\mathrm{AP\,ML}}^2\right)\right]^{1/2} \tag{16}$$

where $s_{\mathrm{AP\,ML}}$ is the covariance.

$$s_{\mathrm{AP\,ML}} = 1/N \sum \mathrm{AP}[n]\mathrm{ML}[n]. \tag{17}$$

The 95% confidence ellipse area is found by substituting (16) into (14) and (15), and then simplifying the product to yield

$$\mathrm{AREA-CE} = \pi ab = 2\pi F_{.05[2,n-2]}\left[s_{\mathrm{AP}}^2 s_{\mathrm{ML}}^2 - s_{\mathrm{AP\,ML}}^2\right]^{1/2}. \tag{18}$$

3) Time-Domain "Hybrid" Measures: Hybrid time-domain measures model the stabilogram with a combination of distance measures. Sway area (AREA-SW) estimates the area enclosed by the COP path per unit of time. This measure is approximated by summing the area of the triangles formed by two consecutive points on the COP path and the mean COP [13]. Sway area is dependent on the distance from the mean COP and the distance traveled by the COP, and can be conceptualized as proportional to the product of mean distance and mean velocity.

$$\mathrm{AREA-SW} = \frac{1}{2T}\sum_{n=1}^{N-1} |\mathrm{AP}[n+1]\mathrm{ML}[n] - \mathrm{AP}[n]\mathrm{ML}[n+1]|. \tag{19}$$

The mean frequency (MFREQ) is the rotational frequency, in revolutions per second or Hz, of the COP if it had traveled the total excursions around a circle with a radius of the mean distance [12]. This measure is proportional to the ratio of the mean velocity to the mean distance. The mean frequency has also been computed with the rms distance rather than the mean distance [20]

$$\mathrm{MFREQ} = \frac{\mathrm{TOTEX}}{2\pi\mathrm{MDIST}\,T} = \frac{\mathrm{MVELO}}{2\pi\mathrm{MDIST}}. \tag{20}$$

The mean frequency-AP ($\mathrm{MFREQ_{AP}}$) is the frequency, in Hz, of a sinusoidal oscillation with an average value of the mean distance-AP and a total path length of total excursions-AP [13].

$$\mathrm{MFREQ_{AP}} = \frac{\mathrm{TOTEX_{AP}}}{4\sqrt{2}\mathrm{MDIST_{AP}}\,T} = \frac{\mathrm{MVELO_{AP}}}{4\sqrt{2}\mathrm{MDIST_{AP}}}. \tag{21}$$

The fractal dimension (FD) is a unitless measure of the degree to which a curve fills the metric space which it encompasses. We have adopted [27] an algorithm which was developed to quantify the degree of convolution, or irregularity, of planar curves composed of connected line segments [16]. The original application of this algorithm was to numerically categorize cell growth paths. One of the fundamental assumptions in the computation of the fractal dimension is the size and shape of the limiting area of the planar curve. The original algorithm and two variations were computed to determine if the usefulness of the fractal dimension in identifying age-related changes in postural steadiness was dependent on the complexity of the associated model for the area enclosed by the stabilogram.

$$\mathrm{FD} = \log(N)/\log(Nd/\mathrm{TOTEX}). \tag{22}$$

In the original description of this algorithm, d represents the planar diameter of the curve, or the maximum distance between any two points. Following this derivation, fractal dimension-PD models the area of the stabilogram with a circle of diameter range, which includes all of the points on the COP path. Fractal dimension-PD generally over estimates the area enclosed by the stabilogram. The discrepancy between the actual area and that modeled with the range as the diameter of a circular area is dependent on the extent to which transient aberrations occur in the COP path from the central core. The fractal dimension was also evaluated with two statistical estimates of the stabilogram area, which are more accurate estimates of the actual area than the estimate based on the planar diameter.

Fractal dimension-CC is based on the 95% confidence circle described in (12) and (13), which models the area of the stabilogram with a circle that includes approximately 95% of the points on the COP path. Fractal dimension-CC is computed by replacing d in (22) with

$$d_{\mathrm{FD-CC}} = 2(\mathrm{MDIST} + z_{.05}s_{\mathrm{RD}}). \tag{23}$$

Fractal dimension-CE models the area of the stabilogram with the 95% confidence ellipse described in (14)–(17). For a stabilogram that is nearly circular in shape, fractal dimension-CC and fractal dimension-CE will be based on similar estimates of the stabilogram area. The area of atypical stabilograms and those obtained for a single foot, such as from a dual force plate balance platform, will be modeled more accurately with the 95% confidence ellipse than the 95% confidence circle. Fractal dimension-CE is computed by replacing d in (22) with

$$\begin{aligned} d_{\mathrm{FD-CE}} &= [2a\ 2b]^{1/2} \\ &= \left[8F_{.05[2,n-2]}\left(s_{\mathrm{AP}}^2 s_{\mathrm{ML}}^2 - s_{\mathrm{AP\,ML}}^2\right)^{1/2}\right]^{1/2}. \end{aligned} \tag{24}$$

4) Frequency Domain Measures: A variety of qualitative and quantitative methods have been used to characterize the frequency distribution of the displacement of the COP [15], [32]. The frequency domain measures described here were selected for their ability to characterize the area or shape of the power spectral density, $G(f)$. The power spectral density of the AP, ML, and RD time series was computed using the sinusoidal multitaper method [34] with 8 tapers. In this method, orthonormal sinusoidal tapers are applied to the entire data set, rather than applying a single taper to multiple segments of the data, as in weighted overlapped segment methods. In terms of leakage, variance, and resolution, multitaper spectral estimation methods have performance advantages over weighted overlapped segment methods [3].

The frequency-domain measures were calculated for the frequency range from 0.15 to 5.0 Hz. The first two frequency points past the dc component (0.05 and 0.10 Hz) were not included in the analysis of the power spectral densities. These points represent events that occur once every 10 or 20 seconds, and probably do not provide significant information about the postural control system. Thus, the summations in (25) were computed with $i = 3$ and $j = 100$. The measures are defined for the AP, ML, or RD time series with the substitution of the corresponding power spectral density, $G_{\mathrm{AP}}(f)$, $G_{\mathrm{ML}}(f)$, or $G_{\mathrm{RD}}(f)$. Δf is the frequency increment in the discrete power spectral density estimate, $G[m]$. The spectral moments, μ_k, are defined [45] as

$$\mu_k = \sum_{m=i}^{j} (m\Delta f)^k G[m]. \tag{25}$$

The total power (POWER) is the integrated area of the power spectrum. Theoretically, if all power is accounted for, this is the mean square value of the time series.

$$\mathrm{POWER} = \mu_0. \tag{26}$$

The 50% power frequency, the median power frequency or the frequency below which 50% of the total power is found, is $u\Delta f$ where u is the smallest integer for which

$$\sum_{m=i}^{u} G[m] \geq 0.50\mu_0. \tag{27}$$

The 95% power frequency, the frequency below which 95% of the total power is found, is $v\Delta f$ where v is the smallest integer for which

$$\sum_{m=i}^{v} G[m] \geq 0.95\mu_0. \tag{28}$$

The centroidal frequency (CFREQ) is the frequency at which the spectral mass is concentrated, which is the square root of the ratio of the second to the zeroth spectral moments [47]. The centroidal frequency is also referred to as the zero crossing frequency, or mean rate of zero crossings, which is one-half the mean number of zero crossings per second of the time series [1].

$$\mathrm{CFREQ} = [\mu_2/\mu_0]^{1/2}. \tag{29}$$

The frequency dispersion (FREQD) is a unitless measure of the variability in the frequency content of the power spectral density [47]. The frequency dispersion is zero for a pure sinusoid and increases with spectral bandwidth to a maximum of one.

$$\mathrm{FREQD} = \left[1 - \mu_1^2/\mu_0\mu_2\right]^{\frac{1}{2}}. \tag{30}$$

C. Statistical Analysis

All statistical procedures were conducted with SYSTAT (SYSTAT, Inc., Evanston, IL). A total of 36 measures were computed for each subject trial. Descriptive statistics and box plots were reviewed for all measures and Romberg ratios within each age group. Pearson correlation coefficients were computed for all eyes-open and eyes-closed measures using the data pooled from the two age groups. A univariate repeated-measures analysis of variance (ANOVA) with a grouping factor for age was performed on each measure [17], [48]. Subsequent individual comparisons were conducted using the between-subjects and within-subjects variation terms from the repeated-measures ANOVA [23]. Individual comparisons were conducted to assess the differences in the measures between the age groups within each condition (eyes-open or eyes-closed), and between the conditions within each age group. To control for the number of univariate statistical tests conducted, the Waller–Duncan Multiple Comparisons Procedure was used [11]. Also, a probability level of $p \leq 0.01$ was accepted as indicative of a statistically significant difference in the individual comparisons, although probabilities $0.05 \leq p < 0.01$ are reported.

III. Results

Representative graphs of the AP, ML, and RD time series, and the corresponding stabilogram for a young adult with eyes-open, are shown in Fig. 1(a) through Fig. 1(d), respectively. The means and standard deviations of all measures and the corresponding Romberg ratios within each age group are listed in Table I. The results of the individual comparisons of the differences in the measures between the age groups within each condition (eyes open or eyes closed), and between the conditions within each age group are also listed in Table I. Although the probabilities for $0.05 \leq p < 0.01$ are listed in Table I, only comparisons with $p \leq 0.01$ were considered indicative of a statistically significant difference between the age groups or eye conditions. In this section, successive listings of the same base measure are indicated with an apostrophe (').

Significant differences between the young adult and elderly adult age groups were found only with eyes open for range and '-AP. Differences between the age groups were found only with eyes closed for sway area, mean frequency, fractal dimension-PD, '-CC, '-CE, total power-RD, and centroidal frequency-RD. Age-related differences were found under both eyes-open and eyes-closed conditions for mean velocity, '-AP, mean frequency-AP, total power-AP, 95% power frequency-RD, '-AP, and centroidal frequency-AP.

The mean of every measure for which a significant difference was found between the two age groups, for either eyes open or eyes closed, was greater for the elderly adult group than for the young adult group. The differences between the two age groups were greater in number and generally statistically stronger with eyes closed than with eyes open. Of the nine measures for which a significant difference was found between the age groups with eyes open, the probability level was $p \leq 0.0001$ for only one, mean velocity-AP. In contrast, the probability level was $p \leq 0.0001$ for eight of the 14 measures for which a significant difference was found between the age groups with eyes closed.

Differences between the eyes-open and eyes-closed conditions were found only in the young adult group for mean distance, '-AP, rms distance, '-AP, range, '-AP, 95% confidence circle area, and 95% confidence ellipse area. These

TABLE I

COP-Based Measures of Postural Steadiness Were Computed for a Group of Healthy Young Adults ($n = 20$; 21–35 Years) and a Group of Healthy Elderly Adults ($n = 20$; 66–70 Years) Under Eyes-Open (EO) and Eyes-Closed (EC) Conditions. The Values Shown Are the Mean ± Standard Deviation for the EO and EC Conditions and the Romberg Ratio (EC/EO). AP Is the Anterior-Posterior COP Displacement Time Series, ML Is the Medial-Lateral COP Displacement Time Series, and RD Is the Resultant Distance Time Series, Which Is the Distance From Each COP Point to the Mean COP. A Repeated-Measures ANOVA with a Grouping Factor for Age Was Conducted on Each Measure. Individual Comparisons Were Conducted Using the Variation Terms From the Repeated-Measures ANOVA. Probabilities Listed in the EO and EC Columns Are for Tests Between the Age Groups Within an EO or EC Condition. Probabilities Listed in the YA (Young Adult) and EA (Elderly Adult) Columns Are for the Differences Between the Eye Conditions Within an Age Group. The Pearson Correlation Coefficient (r) Between the Measures in Each Correlation Group (Corr Grp) Were $r \geq 0.90$ for Both EO and EC Conditions Except As Listed Below: +, $p < 0.0500$; ‡, $p \leq 0.0100$; ‡‡, $p \leq 0.0010$; and ‡‡‡, $p \leq 0.0001$

	Young Adult			Elderly Adult			Age		Eye		Corr
Measure	Eyes-Open	Eyes-Closed	Romberg	Eyes-Open	Eyes-Closed	Romberg	EO	EC	YA	EA	Grp
mean distance (mm)	3.12±1.11	3.85±1.65	1.28±0.45	4.22±1.24	4.48±1.52	1.10±0.33	+		‡		A
mean distance-AP (mm)	2.42±0.97	3.10±1.29	1.44±0.81	3.19±1.01	3.63±1.17	1.19±0.41	+		‡	+	B
mean distance-ML (mm)	1.50±0.77	1.66±0.95	1.10±0.37	2.04±1.05	1.93±0.99	1.11±0.64					C
rms distance (mm)	3.56±1.20	4.39±1.81	1.29±0.47	4.85±1.42	5.12±1.70	1.09±0.32	+		‡		A
rms distance-AP (mm)	2.95±1.08	3.82±1.54	1.45±0.81	3.98±1.22	4.45±1.42	1.16±0.36	+		‡		B
rms distance-ML (mm)	1.85±0.91	2.06±1.17	1.10±0.35	2.54±1.34	2.41±1.23	1.12±0.66					C
range (mm)	14.3±4.34	18.0±7.14	1.35±0.60	21.6±6.84	22.5±7.40	1.06±0.31	‡		‡		A,D
range-AP (mm)	13.3±4.27	17.7±6.97	1.49±0.83	20.1±6.07	21.1±6.93	1.08±0.33	‡		‡‡		B,D
range-ML (mm)	8.48±3.89	9.79±5.42	1.16±0.43	12.5±7.50	12.3±6.84	1.17±0.70	+				C
mean velocity (mm/s)	6.90±1.79	8.89±2.86	1.29±0.24	12.2±4.49	16.2±6.43	1.35±0.38	‡‡	‡‡‡	‡	‡‡‡	E
mean velocity-AP (mm/s)	4.92±1.34	6.72±2.18	1.38±0.28	9.86±3.63	13.5±5.26	1.41±0.44	‡‡‡	‡‡‡	‡‡	‡‡‡	E
mean velocity-ML (mm/s)	3.82±1.19	4.43±1.65	1.17±0.28	5.34±2.56	6.27±3.70	1.23±0.48		+		+	F
95% conf. circle area (mm^2)	120±70.3	193±146	1.91±1.46	224±128	251±157	1.26±0.68	+		‡		A
95% conf. ellipse area (mm^2)	99.1±66.9	162±140	1.70±1.26	191±125	207±152	1.36±0.97	+		‡		A
sway area (mm^2/s)	7.16±4.27	11.3±8.11	1.62±0.83	16.3±12.1	21.4±17.4	1.52±0.95	+	‡	+	‡	F
mean frequency (Hz)	0.374±0.092	0.400±0.120	1.11±0.38	0.470±0.130	0.577±0.138	1.26±0.26	+	‡‡‡		‡‡‡	G
mean frequency-AP (Hz)	0.398±0.140	0.423±0.149	1.17±0.54	0.565±0.195	0.664±0.172	1.23±0.29	‡	‡‡‡		‡‡	I
mean frequency-ML (Hz)	0.524±0.214	0.567±0.227	1.15±0.41	0.506±0.166	0.591±0.170	1.23±0.38				‡	J
fractal dimension-PD	1.434±0.067	1.442±0.073	1.01±0.07	1.470±0.067	1.543±0.058	1.05±0.04		‡‡‡		‡‡‡	H
fractal dimension-CC	1.487±0.069	1.504±0.089	1.01±0.07	1.554±0.081	1.628±0.072	1.05±0.04	+	‡‡‡		‡‡‡	G,H
fractal dimension-CE	1.523±0.071	1.548±0.104	1.02±0.05	1.588±0.096	1.668±0.090	1.05±0.06	+	‡‡		‡‡‡	G
total power-RD	6.66±3.67	10.4±9.82	1.65±1.27	13.0±7.40	18.3±12.7	1.70±1.20	+	‡	+	‡	
total power-AP	8.88±5.12	16.8±11.8	2.29±2.07	20.5±13.1	28.1±15.0	1.56±0.83	‡	‡	+	+	D
total power-ML	4.35±3.49	6.17±5.22	1.49±1.02	9.38±10.0	9.57±11.0	1.69±1.81					C,F
50% power frequency-RD (Hz)	0.285±0.075	0.320±0.106	1.18±0.48	0.353±0.152	0.403±0.134	1.22±0.37		+	+	‡	
50% power frequency-AP (Hz)	0.275±0.085	0.300±0.093	1.16±0.45	0.355±0.141	0.388±0.120	1.15±0.30	+	+			
50% power frequency-ML (Hz)	0.355±0.143	0.380±0.144	1.13±0.35	0.353±0.140	0.400±0.132	1.22±0.43				+	
95% power frequency-RD (Hz)	0.925±0.189	1.05±0.298	1.15±0.30	1.27±0.371	1.47±0.430	1.20±0.32	‡	‡‡	+	‡‡	K
95% power frequency-AP (Hz)	0.928±0.204	0.985±0.313	1.08±0.28	1.29±0.349	1.45±0.430	1.14±0.24	‡	‡‡‡		‡	L
95% power frequency-ML (Hz)	0.993±0.329	1.10±0.341	1.17±0.41	1.07±0.314	1.20±0.355	1.16±0.32				+	M
centroidal frequency-RD (Hz)	0.534±0.097	0.574±0.130	1.09±0.24	0.656±0.174	0.754±0.180	1.18±0.25	+	‡‡		‡‡	K
centroidal frequency-AP (Hz)	0.509±0.091	0.538±0.134	1.08±0.26	0.659±0.167	0.748±0.177	1.16±0.22	‡	‡‡‡		‡‡	I,L
centroidal frequency-ML (Hz)	0.604±0.167	0.638±0.185	1.08±0.26	0.592±0.154	0.660±0.164	1.15±0.28				+	J,M
frequency dispersion-RD	0.666±0.040	0.665±0.042	1.00±0.09	0.675±0.065	0.672±0.041	1.00±0.08					
frequency dispersion-AP	0.668±0.049	0.659±0.039	0.99±0.08	0.672±0.054	0.672±0.040	1.00±0.08					
frequency dispersion-ML	0.667±0.072	0.666±0.052	1.01±0.11	0.649±0.058	0.644±0.053	1.00±0.09					

All correlations within a correlation group are $r \geq 0.90$ except group A: $r > 0.86$ between *range* and *95% confidence ellipse area* for EO and EC; group C: $r > 0.88$ between *mean distance-ML* and *total power-ML* for EO; group F: $r > 0.88$ between *sway area* and *total power-ML* for EC; group G: $r > 0.85$ between *fractal dimension-CC* and *fractal dimension-CE* for EO and EC.

measures are all time domain distance or area measures. The mean Romberg ratios for these measures were greater for the young adult group than for the elderly adult group. Differences between the eyes-open and eyes-closed conditions were found only in the elderly adult group for sway area, mean frequency, '-AP, '-ML, fractal dimension-PD, '-CC, '-CE, total power-RD, 50% power frequency-RD, 95% power frequency-RD, '-AP, centroidal frequency-RD, and '-AP. These measures are all time domain hybrid or frequency domain measures. The mean Romberg ratios for these measures were greater for the elderly adult group than for the young adult group. Differences between eyes open and eyes closed were found in both age groups for mean velocity and '-AP.

The differences between the eyes-open and eyes-closed conditions were greater in number and generally statistically stronger for the elderly adult group than for the young adult group. None of the ten measures for which a significant difference was found between the eye conditions for the young adult group had a probability level of $p \leq 0.0001$. In contrast, the probability level was $p \leq 0.0001$ for six of the 15 measures

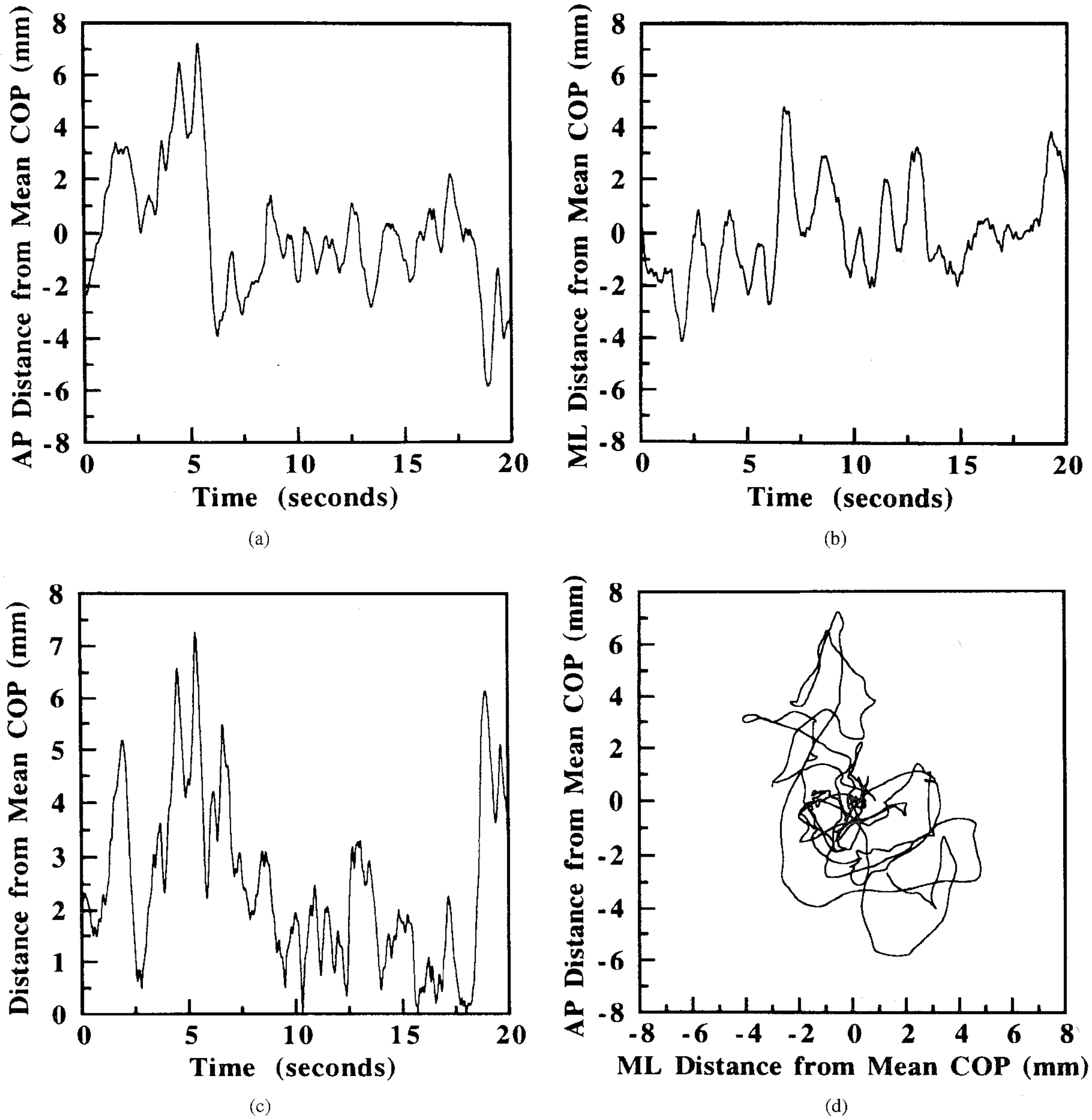

Fig. 1. Representative COP time series for a healthy young adult during quiet standing for 20 seconds with eyes-open: (a) AP time series of the displacement from the mean COP, (b) ML time series of the displacement from the mean COP, (c) RD time series is the distance from each COP point to the mean COP, and (d) Stabilogram or planar trajectory of the COP.

for which a significant difference was found between the eye conditions for the elderly adult group.

The measures for which the Pearson correlation coefficients were $r \geq 0.90$ with both eyes open and eyes closed were grouped and listed in Table I. The following groups were identified.

A) RMS distance: mean distance: range: 95% confidence circle area: 95% confidence ellipse area ($r > 0.86$ between range and 95% confidence ellipse area for eyes open and eyes closed).
B) RMS distance-AP: mean distance-AP: range-AP.
C) RMS distance-ML: mean distance-ML: range-ML: total power-ML ($r > 0.88$ between mean distance-ML and total power-ML for eyes open);
D) Range: range-AP: total power-AP.
E) Mean velocity: mean velocity-AP.
F) Mean velocity-ML: sway area: total power-ML ($r > 0.88$ between sway area and total power-ML for eyes closed).
G) Mean frequency: fractal dimension-CC: fractal dimension-CE ($r > 0.85$ between fractal dimension-CC and fractal dimension-CE for eyes open and eyes closed).
H) Fractal dimension-PD: fractal dimension-CC.
I) Mean frequency-AP: centroidal frequency-AP.
J) Mean frequency-ML: centroidal frequency-ML.
K) 95% power frequency-RD: centroidal frequency-RD.
L) 95% power frequency-AP: centroidal frequency-AP.
M) 95% power frequency-ML: centroidal frequency-ML.

The correlations between measures were generally greater for the eyes-closed measures than the eyes-open measures. Fifty-one of the correlations were $r \geq 0.90$ with eyes closed, compared to 34 with eyes open. For the ten measures with a composite component and AP and ML directional components, the correlation between the composite and AP components was larger than the correlation between the composite and ML components, which was larger than the correlation between the AP and ML components. These correlations were greater with eyes closed than with eyes open. The mean correlation was 0.85 ± 0.10 (s.d.) with eyes open and 0.90 ± 0.09 with eyes closed between the composite and AP measures; 0.51 ± 0.28 with eyes open and 0.62 ± 0.21 with eyes closed between the composite and ML measures; 0.28 ± 0.22 with eyes open and 0.49 ± 0.20 with eyes closed between the AP and ML measures.

IV. Discussion

The primary objective of this investigation was to evaluate the relative sensitivity of COP-based measures to age-related changes in postural steadiness, by comparing a variety of measures in a group of healthy young adults and a group of healthy elderly adults under both eyes-open and eyes-closed conditions. Time domain distance, area, and hybrid measures and frequency domain measures were evaluated. Measures were computed using both the AP and ML time series, or only one of these directional components. These measures represent a variety of traditional and relatively new methods for characterizing the COP path during an evaluation of postural steadiness. Composite measures, which are based on both the AP and ML directional components, are preferred when the placement of the feet on the force plate is not constrained, since these measures are not sensitive to the orientation of the base-of-support with respect to the axes of the force plate. AP and ML measures are most indicative of the true directional components when the foot placement is constrained to a position aligned with axes of the force plate. However, this may lead to testing some subjects in a stance that is not representative of their normal stance [9].

To identify the measures most sensitive to age, a repeated-measures ANOVA with a grouping factor for age was conducted on each measure, and subsequent individual comparisons were computed using the between-subjects and within-subjects variations from the repeated-measures ANOVA. This procedure was designed to identify measures with significant differences between the two age groups within one or both of the eye conditions, and between the eye conditions within one or both of the age groups. The correlation coefficients between the measures for the eyes-open and eyes-closed conditions were evaluated to determine which measures are essentially quantifying the same information regarding postural steadiness. As expected, the age-related changes and differences between eye conditions identified with measures within a highly correlated group agreed closely. Moreover, the number of significant differences found across different correlation groups, as evident in Table I, indicates that these significant differences were not due to chance.

Correlation coefficients were used to identify groups of highly correlated measures. This information is useful in selecting particular measures to characterize postural steadiness. It is redundant to compute more than one measure from any group of highly correlated measures. This information allows researchers and clinicians to choose a group of uncorrelated measures. More than one measure may be necessary to adequately characterize multiple aspects of postural steadiness. For example, Maki *et al.* [20] used rms distance-AP, range-AP, mean velocity-AP, mean frequency-AP, centroidal frequency-AP, and frequency dispersion-AP to compare postural steadiness with eyes-open in a group of young adults and a group of elderly adults. Based on the correlation groups identified in this study, the group of measures used by Maki *et al.* represent a good cross section of uncorrelated measures, except for the high correlations found between rms distance-AP and range-AP, and between mean frequency-AP and centroidal frequency-AP.

The results of this study are generally in agreement with the findings of Maki *et al.* [20]. As in this study, Maki *et al.* found age-related changes in both mean velocity-AP and range-AP, with stronger changes in the former. Also as in this study, Maki *et al.* did not find age-related changes in rms distance-AP. In contrast to their findings, the current study found age-related changes in mean frequency-AP, but not in frequency dispersion-AP. The reasons for these differences in findings are unclear, but may be due to differences in methodology. Maki *et al.* computed mean frequency-AP using rms-distance-AP, whereas mean distance-AP was used in this study. These measures are highly correlated so it is unlikely that this would result in a significant difference. Further comparison between these studies is difficult because the portion of the 77-s trial selected for analysis, the type of filtering used, and the frequency range over which the measures were computed were not reported by Maki *et al.*

The time domain distance and area measures, which include rms distance, mean distance, range, 95% confidence circle area, and 95% confidence ellipse area, are all estimates of the size of the stabilogram and were found to be highly correlated. These measures identified differences between the eyes-open and eyes-closed conditions in young adults that were not found in elderly adults. Also, these measures indicated a trend toward differences between the young and elderly adults with eyes-open but not with eyes-closed. Mean velocity and mean velocity-AP were the only measures that identified age-related changes in both eye conditions, and differences between eye conditions in both age groups. These two measures were also highly correlated. Mean velocity increased with age and was greater with eyes closed than with eyes open. This was associated with an increase in the size of the stabilogram for the young adults but not for the elderly adults.

Mean distance and rms distance have been related to the effectiveness of, or the stability achieved by, the postural control system; and mean velocity has been related to the amount of regulatory activity associated with this level of stability [13], [20]. The results of this study indicate that mean distance, rms distance, and other measures of the size of the stabilogram do not change significantly with age, in contrast to the marked age-related changes found in mean velocity. The subjects in this study were all healthy individuals who did not have difficulty maintaining standing balance. These subjects may have all attained a similar level of steadiness, but the elderly subjects may have required significantly more postural control activity to achieve this level of steadiness.

The time domain hybrid measures include sway area, mean frequency and fractal dimension. These measures are derived from different models of the COP dynamics, but all relate the area or size of the stabilogram to the mean velocity of, or total distance traveled by, the COP. According to the theory described above regarding the size of the stabilogram and the mean velocity, the hybrid measures are quantifying the relationship between the activity of the postural control system and the level of stability achieved. The hybrid measures identified strong age-related changes with eyes-closed, but only a trend toward age-related changes with eyes-open. The hybrid measures identified differences between the eyes-open and eyes-closed conditions for the elderly adults, but not for the young adults. Also, the hybrid measures were not highly correlated with mean velocity. The strong age-related changes in the hybrid measures with eyes-closed, and the strong differences between eyes-open and eyes-closed in the elderly adult group, may be due to the strong changes in mean velocity coincident with a lack of changes in the distance and area measures. Thus, the level of stability achieved may have been the same but the activity of the postural control system may have increased significantly.

The frequency domain measures of total power, 95% power frequency, and centroidal frequency based on the RD and AP time series identified age-related differences with eyes-open and eyes-closed, though the differences were stronger with eyes-closed than with eyes-open. The 95% power frequency, which is an estimate of the extent of the spectral content, and the centroidal frequency, which is an estimate of the equivalent zero crossing frequency, were highly correlated. Frequency dispersion was the only measure which did not identify differences between the age groups or eye conditions. These findings indicate that the total power, 95% power frequency, and centroidal frequency increase with age primarily with eyes-closed, but the relative spread about the central frequency remains relatively constant.

Four of the measures included in this study, fractal dimension 95% confidence circle area, 50% power frequency, and 95% power frequency, had little or no prior use in characterizing postural steadiness. The three fractal dimension measures were based on different models of the stabilogram area but all identified the same differences related to age and eye condition. The fractal dimension measures were generally highly correlated with each other and with mean frequency. The computation of both fractal dimension and mean frequency, although based on very different models, is probably redundant. The 95% confidence circle area is a relatively simple estimate of the area of the stabilogram based on a circular model. This measure, the other area measure, 95% confidence ellipse area, and the time domain distance measures were highly correlated and did not identify age-related differences in postural steadiness. The 50% power frequency identified trends in the differences between the age groups and eye conditions that were generally not significant. The 95% power frequency, which is readily interpretable as an estimate of the extent of the frequency content of the time series, identified age-related changes in both eye conditions, and differences between the eye conditions in the elderly adult group.

No age-related changes were found in any of the measures based on the ML directional component of the COP. RMS distance-ML with eyes blindfolded was found to be the single best predictor of future falling risk in a comparison of a variety of balance testing methodologies and measures, which included static and dynamic posturography as well as clinical balance tests [22]. As in the present study though, age-related changes were not found in this measure. The correlations between the composite and AP directional component measures were greater than the correlations between the composite and ML measures, as can be expected since the AP component is markedly larger than the ML component for all of the distance measures and total power. Also, the correlations between the AP and ML measures were relatively low. These findings suggest that ML postural control activity does not necessarily increase coincident with the increases in AP activity related to age.

Further research is necessary to explain why the differences between the eyes-open and eyes-closed conditions in the young adults were identified with time domain distance and area measures, but the differences between the eye conditions in the elderly adults were identified with time domain hybrid and frequency domain measures. This may indicate that the strategy used to compensate for the deprivation of visual information changes with age, and consequently is characterized by a different set of measures.

Postural dyscontrol in the elderly is a heterogeneous condition, reflecting general age-related deficits in the postural control system, and possibly specific pathologies which may be unique to each individual and are often subclinical [12]. This investigation controlled for only one grouping factor—age. Differences between these age groups may also be associated with other factors, such as gender [18], base of support, and individual-specific changes with age or pathological processes. The questions of if, and how, measures of postural steadiness should be normalized to the base-of-support remains unresolved. Maki *et al.* [20] reported that normalizing measures to the AP length of the feet had little effect on the age-related differences identified in the study. One of the major concerns with normalizing measures to the base-of-support is whether an anatomical or functional dimension should be used [45].

The healthy elderly group in this study consisted of individuals living independently in the community with a relatively active lifestyle. In more impaired subject groups, postural dyscontrol may be dominated by the individual-specific pathologies, and general age-related deficits may be less pronounced. Fernie *et al.* [6] did not find age- or gender-related changes in the mean speed of movements measured at the pelvis for a group of 205 institutionalized subjects ranging in age from 63 to 99 years. However, Maki *et al.* [22] found age-related changes in mean velocity and mean frequency for a group of 100 subjects ranging in age from 62 to 96 years; most of these subjects experienced one or more falls during a one year prospective monitoring period.

This study identified COP-based measures of postural steadiness that can be expected to change with age. This information will be useful to researchers and clinicians who are using these measures to evaluate postural steadiness, or to evaluate the risk of falling in the elderly population. In these applications, it may be useful to identify measures that are outside of the expected range, which may be related to age, as shown in this study. Studies have associated measures of postural steadiness with the incidence of falls [2], [29], although this was only suggestive of a tendency to fall in another study [6]. Other studies have found that postural steadiness measures can be useful in discriminating between fallers and nonfallers [22], and predicting the risk of falling [44]. Also, an association has been reported between postural steadiness measures and a clinical mobility index, which was validated against incident falls in a long-term care population [19].

The results of this study indicate that multiple measures are probably necessary to adequately characterize differences between groups of young and elderly adults, and between eyes-open and eyes-closed trial conditions within these groups. Based on the findings of this study, the following COP-based measures of postural steadiness are recommended for use in similar studies: mean velocity, one of the time domain distance or area measures, such as rms distance, one of the time domain hybrid measures, such as mean frequency, and one of the frequency domain measures, such as centroidal frequency. This group of measures is a subset of those used by Maki *et al.* [20].

The relative sensitivity of postural steadiness measures to changes related to age identified in this study does not imply sensitivity to changes related to neurologic disease, orthopedic disease, or other pathologies affecting the postural control system. We are expanding the findings of this study in several directions. The measures identified in the present study as being sensitive to age will be evaluated in a discriminant analysis to determine the reliability of predicting membership in one of the two age groups using a set of these measures. This follows from the distinct correlation groups identified here and listed in Table I. Measures that change with age and are not highly correlated with each other may characterize different aspects of postural steadiness, and consequently may account for different portions of the variance between the two age groups. A discriminant analysis of these measures may provide further insight into the extent to which general age-related changes in postural control contribute to postural dyscontrol in the elderly. These measures are also under evaluation in a larger group of subjects representing a more continuous distribution of ages to determine if these changes develop gradually with age, or only become apparent above a particular age.

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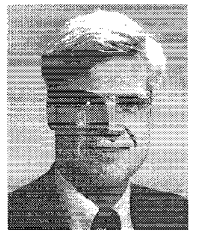

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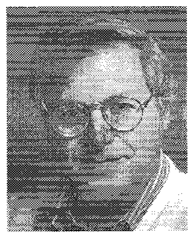

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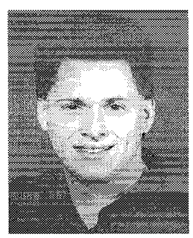

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