Journal of Biomechanics 41 (2008) 406–411

JOURNAL OF BIOMECHANICS

www.elsevier.com/locate/jbiomech
www.JBiomech.com

Direct parameterization of postural stability during quiet upright stance: Effects of age and altered sensory conditions

Sunwook Kim[a], Maury A. Nussbaum[a,b,*], Michael L. Madigan[b,c]

[a]Department of Industrial and Systems Engineering, Virginia Tech 250, Durham Hall (0118), Blacksburg, VA 24061, USA
[b]School of Biomedical Engineering and Sciences, Virginia Tech, Blacksburg, VA 24061, USA
[c]Department of Engineering Science and Mechanics, Virginia Tech, Blacksburg, VA 24061, USA

Accepted 22 August 2007

Abstract

The purpose of this study was to determine the relationship between measures of local dynamic stability (LDS) during upright stance and both descriptive measures of postural sway and a scaling index (α) derived from detrended fluctuation analysis. Center of pressure (COP) time series were obtained from healthy participants (16 young and 16 older) during upright quiet stance. Vision and somatosensation were altered by eye closure and standing on a compliant surface, respectively. A non-linear time-series analysis method was used to compute three LDS parameters from the COP data: A which was defined as the COP excursion range in state space, and τ_S and τ_L which were defined as the divergence rates over short- and long-term timescales, respectively. LDS parameters, descriptive COP measures, and α had generally consistent sensitivities to age and/or altered sensory conditions. Age x sensory condition interactions, however, had distinct effects on LDS parameters compared to the other COP-based measures. Older individuals exhibited faster divergence rates while having similar magnitudes of A, compared to young individuals. These results suggest that older individuals stiffen the musculoskeletal system via increased muscle activity, perhaps as an age-related postural adaptation. In addition, correlations between LDS parameters and other COP measures were relatively small ($r^2 \leqslant 0.29$). Hence, LDS parameters (A, τ_S and τ_L) provide distinct information on postural control and stability, supplementing other COP-based measures.

Keywords: Postural control; Stability; Non-linear dynamics; Aging; Detrended fluctuation analysis

1. Introduction

In quiet upright stance, the center of pressure (COP) reflects the collective postural control to maintain balance within the base-of-support (Prieto et al., 1993; Winter, 1995). A variety of descriptive COP-based measures (e.g., mean velocity, mean power frequency, etc.) have been used to examine the postural control system, and have been shown to detect differences related to age (Du Pasquier et al., 2003; Prieto et al., 1993), pathological conditions (Nies and Sinnott, 1991) and altered sensory inputs (Baratto et al., 2002). In these and related studies, postural stability was inferred empirically from systematic changes in descriptive COP measures. However, postural stability in quiet upright standing can be considered as a type of local dynamic stability (LDS); i.e., the sensitivity of COP dynamics to small perturbations such as internal neural noise and/or altered sensory information. LDS is unlikely represented by descriptive measures because of the inherent temporal averaging involved.

Application of non-linear time-series analysis techniques has enabled direct quantification of dynamic characteristics of the postural control system. For example, several studies have used the largest Lyapunov exponent (λ_{max}) to characterize an average rate of divergence during standing to assess postural stability. Using such methods, individuals with pathological conditions were found less stable than healthy individuals (Pascolo et al., 2005; Roerdink et al., 2006). Since λ_{max} can be spurious for experimental

*Corresponding author. Department of Industrial and Systems Engineering, Virginia Tech 250, Durham Hall (0118), Blacksburg, VA 24061, USA. Tel.: +1 540 231 6053; fax: +1 540 231 3322.
E-mail address: nussbaum@vt.edu (M.A. Nussbaum).

0021-9290/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2007.08.011

data that are not truly chaotic (Timmer et al., 2000), a recent study (Kang and Dingwell, 2006) parameterized LDS during standing and walking with a double exponential function from trunk kinematic variables. Furthermore, the power-law scaling behavior of COP time series was suggested to have implications in postural stability in that individuals at a higher risk of falls exhibited smaller scaling index values (Norris et al, 2005; Amoud et al., 2007). Nevertheless, whether a relationship exists between LDS and such a scaling index is unclear, and also uncertain are the effects of age and altered sensory conditions on LDS.

The objective of this study was to parameterize the LDS of quiet standing using COP time series and to examine the sensitivity of LDS parameters to different age and sensory conditions (i.e., altered vision and somatosensation). A secondary objective was to examine if LDS parameters are correlated with indirect stability measures (i.e., descriptive COP measures and a scaling index). We hypothesized that LDS parameters, a scaling index and descriptive COP measures would all reflect differences in stability related to different age and sensory conditions, yet the LDS parameters would not be correlated with the scaling index or descriptive COP measures. Confirming this hypothesis would demonstrate that LDS parameters yield distinct information on postural stability under varied age and sensory conditions.

2. Methods

2.1. Participants and experimental procedures

Thirty-two healthy individuals (16 young and 16 older adults, gender balanced in each group) from the university and local community volunteered for a larger study investigating the effects of age and localized muscle fatigue on postural control. The mean (SD) age, height and body mass were 20.9 (1.7) yr, 171.1 (6.8) cm and 67.3 (12) kg for young participants, and 63.2 (5.5) yr, 167.8 (10.6) cm and 77.6 (17.8) kg for older participants, respectively. Participants had no self-reported injuries, illnesses, musculoskeletal disorders or occurrences of falls in the past year. All completed an informed consent procedure approved by the Virginia Tech Institutional Review Board.

Experimental trials involved quiet upright stance in several visual and surface conditions. Participants stood barefoot on a force platform (AMTI OR6-7-1000, Watertown, MA, USA) in a quiet room, and were instructed to stand as still as possible with their feet together and arms at their sides. Visual conditions had two levels: eyes-open (EO) and eyes-closed (EC). In the EO condition, participants were asked to stare at a cross mark that was located at eye height and 75 cm away from their eyes. Surface conditions also had two levels: hard surface (HS) and soft surface (SS). During SS conditions, a 23 mm-thick piece of foam covered the force platform. Three replications of each of the four conditions (two vision × two surface) were performed, in a randomized order, with at least 1 min of rest between each. Repeatability of foot placement was maintained by outlining the feet on poster board placed on top of the force platform. Triaxial ground reaction forces and moments were sampled at 100 Hz. Each trial lasted 75 s, with the initial 10 s and last 5 s removed to avoid initial transients and anticipation effects, respectively.

2.2. COP data reduction and descriptive measures

COP trajectories were computed in both anterior–posterior (AP) and medial–lateral (ML) directions, and were demeaned in the respective directions. Following Prieto et al. (1996), four descriptive COP measures were computed: mean velocity (MV), 95% confidence ellipse area (EA95), and the mean power frequencies (MPF) of the COP time series in the AP (MPF_{AP}) and ML (MPF_{ML}) directions. MPFs were estimated using Welch's power spectrum estimation method. These descriptive measures were normalized using individual anthropometric data (Hof, 1996).

2.3. Detrended fluctuation analysis (DFA), scaling index α

DFA was used to extract α. DFA includes an integration step that transforms a bounded series (COP series) into an unbounded series, which has been suggested to surpass the shortcoming of earlier methods (see Delignières et al., 2003). Fluctuation of the detrended series, $F(n)$, is characterized by the following power law:

$$F(n) \propto n^{\alpha}, \tag{1}$$

where α is the slope of a double logarithm plot of $F(n)$ vs. n. Fractional Gaussian noise (fGn) corresponds to $0<\alpha<1$, fractional Brownian motions (fBm) to $1<\alpha<2$ and Brownian motion to $\alpha = 1.5$ (Delignières et al., 2005). DFA was separately performed on the AP and ML trajectories for $n = 10$–500 (i.e., 0.1–5 s), considering that control mechanisms for standing stability may act over 5 s (Kang and Dingwell, 2006).

2.4. Local dynamic stability parameters

COP dynamics are constrained to a 2-D plane (i.e., the top surface of the force platform). Hence, four state variables (i.e., COP movements in the AP and ML directions and their derivatives) can sufficiently describe the COP dynamics as a second-order system (Pai and Patton, 1996). The state space vector of a COP time series is thus given as

$$S(t_i) = [x(t_i), y(t_i), \dot{x}(t_i), \dot{y}(t_i)], \tag{2}$$

where x and $\dot{x}$, respectively, represent the COP time series and its derivative in the AP direction, y and $\dot{y}$, respectively, represent the COP time series and its derivative in the ML direction, and t_i is a discrete time. Derivatives were numerically obtained using a five-point differentiation (Burden and Faires, 1997). Each variable of $S(t_i)$ was demeaned and normalized to unit variance to account for the different units involved.

For each point on $S(t_i)$, the nearest neighbor was located, with an initial separation from the point of at least twice a fixed time delay (Roerdink et al., 2006). The time delay was computed for each trial using the average displacement method (Rosenstein et al., 1994). Distances (Euclidean norm) were computed to trace the behavior of this pair of neighboring trajectories as a function of time; i.e., the divergence distance (d_i, details in Rosenstein et al., 1993). Subsequently, the mean divergence distance, $\langle d_i \rangle$, was obtained by averaging the logarithm of d_i vectors for all pairs of neighboring trajectories so that $\langle d_i \rangle$ represents how a COP time series in state space responds on average to small perturbations during quiet upright stance. The mean divergence distance (computed over 5 s) of the COP dynamics was parameterized using a double exponential function introduced by Kang and Dingwell (2006):

$$\langle d_i \rangle = A - B_S\, e^{-t/\tau_S} - B_L\, e^{-t/\tau_L}, \tag{3}$$

where A can be considered as the COP excursion range in state space, B_S and B_L as the initial respective excursions over short- and long-term timescales, and τ_S and τ_L as the respective divergence rates over short- and long-term timescales ($\tau_S \ll \tau_L$). The effect of each parameter is illustrated in Fig. 1.

To determine if LDS parameter values were due to auto-correlated Gaussian noise, phase-randomized surrogate data were generated (Theiler et al., 1992), and LDS parameters were computed for surrogate data. The null hypothesis was that LDS parameters would be the same for the original data and the surrogate data.

Separate three-way repeated measures analyzes of variance (ANOVA) were performed on each of the COP measures to determine main and interactive effects of age (Y, young vs. O, older), vision (EO vs. EC), and surface condition (HS vs. SS). Significant effects were followed by post hoc

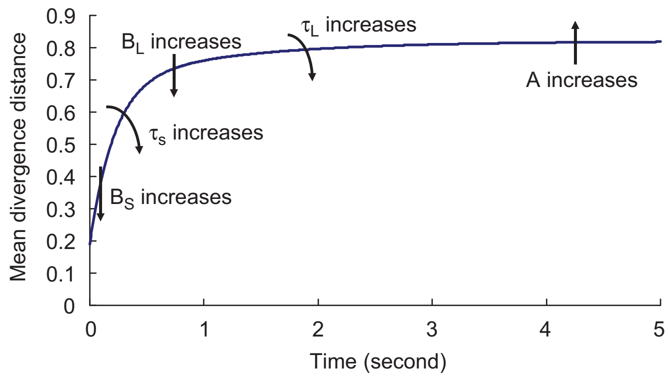

Fig. 1. Effect of each parameter in the exponential fitting function for LDS (Eq. (3)). The function saturates to the excursion range of COP in state space (A); B_S and B_L are the initial excursions over short- and long-term timescales and τ_S and τ_L are the divergence rates over short- and long-term timescales.

pairwise comparisons (Tukey HSD). To quantify the correspondence between the LDS parameters and the other measures, coefficients of determination (r^2) were computed within each age group. No obvious non-linear relationships were apparent between pairs of measures. In addition, separate one-way repeated measures ANOVAs were performed on the LDS parameters for the original COP data and surrogate data within each age group and sensory condition. Statistical significance was concluded when $p \leqslant .05$.

3. Results

3.1. Effects of age, vision and surface conditions

ANOVA results are summarized in Table 1. The exponential fitting function for parameterizing LDS measures (Eq. (3)) achieved $r^2 > 0.9$ across all trials. There were main effects of age, vision and surface, as well as age *x* vision interaction effects on the LDS parameters A and τ_L. Parameter A increased and τ_L decreased with eye closure, but this effect was less evident among O (Fig. 2). Both A and τ_L were smaller during SS than HS. Parameter τ_S was affected by age ($O < Y$) and the vision *x* surface interaction (Fig. 3). Parameter B_L was affected by vision, age *x* vision and the vision *x* surface interaction (YEC = OEC = OEO < YEO = OEC = OEO, and ECSS < ECHS = EOHS = EOSS).

Regarding the scaling index, α_{AP} was affected by vision and surface (ECHS = ECSS < EOHS < EOSS), while α_{ML} was affected by age and vision (YEO = OEO < YEO = OEC < YEC). All values of α_{AP} and α_{ML} were between 1.23 and 1.48, hence, the COP time series can be regarded as sub-diffusive fBm or Brownian motion. Among the descriptive measures, there were main and interaction effects of age, vision and surface on MV (YEO = OEO < YEC = OEO < OEC, YHS = YSS = OHS < OSS and EOHS = EOSS < ECHS < ECSS). EA95 was affected by vision and surface conditions, as well as the age *x* vision interaction (HS < SS and YEO = OEO < YEC < OEC). MPF_{AP} was affected by age, vision and surface condition ($Y < O$, HS < SS and EO < EC) and

Table 1
Main and interactive effects of age, vision and surface conditions on all COP measures

	Age $F_{(1,30)}$	Vision $F_{(1,347)}$	Surface $F_{(1,347)}$	Age *x* vision $F_{(1,347)}$	Age *x* surface $F_{(1,347)}$	Vision *x* surface $F_{(1,347)}$
A	5.70†	10.55†	13.92†	7.54†	2.45	0.06
B_S	0.47	3.63	0.01	1.11	1.11	0.00
τ_S	6.72†	2.33	0.74	0.08	1.72	6.48†
B_L	0.01	14.83†	0.97	3.97†	0.88	7.46†
τ_L	13.96†	97.46†	7.81†	25.98†	1.02	1.94
α_{AP}	2.88	184.47†	3.47	0.99	0.84	7.16†
α_{ML}	5.26†	78.75†	3.07	8.11†	0.28	3.62
MV	8.65†	635.82†	21.88†	55.83†	4.06†	9.26†
EA95	2.78	413.44†	5.36†	27.74†	2.92	1.51
MPF_{AP}	6.01†	219.89†	5.24†	0.83	0.30	1.99
MPF_{ML}	8.00†	1.88	14.86†	1.27	0.23	0.65

A, B_S, B_L, τ_S and τ_L—local dynamic stability parameters; α_{AP} and α_{ML}—scaling indices in AP and ML directions.
MV, mean COP velocity; EA95, 95% confidence ellipse area; MPF_{AP} and MPF_{ML}, mean power frequency.
†Significant at $p \leqslant .05$.

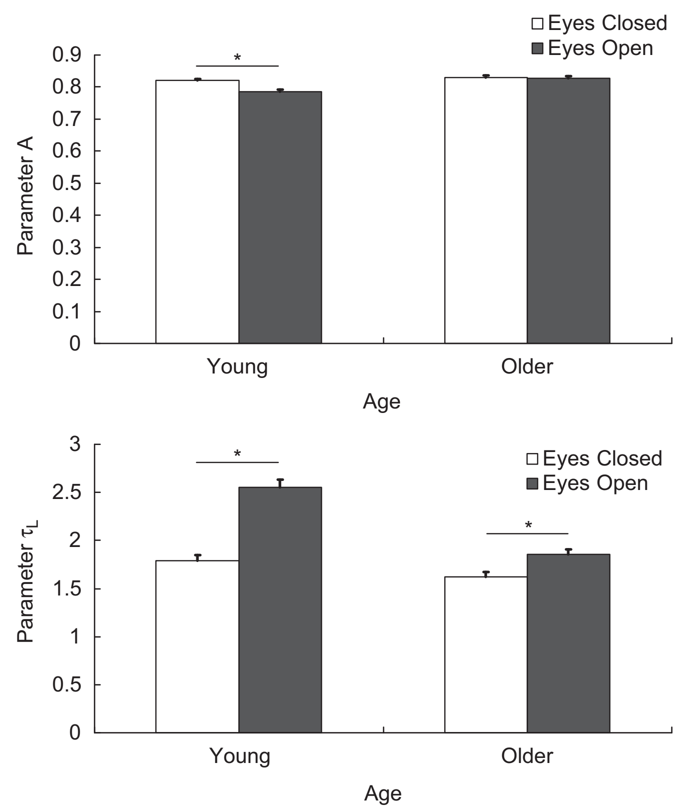

Fig. 2. Effects of age and vision on local dynamic stability parameters A (top) and τ_L (bottom). Effects of age, vision and age *x* vision were significant for both A and τ_L. Significant differences between visual conditions are indicated by * and error bars indicate standard errors.

MPF_{ML} was affected by age and surface condition ($Y > O$ and HS < SS).

The LDS parameters (A and τ_S) for the original and surrogate COP data were significantly different such that

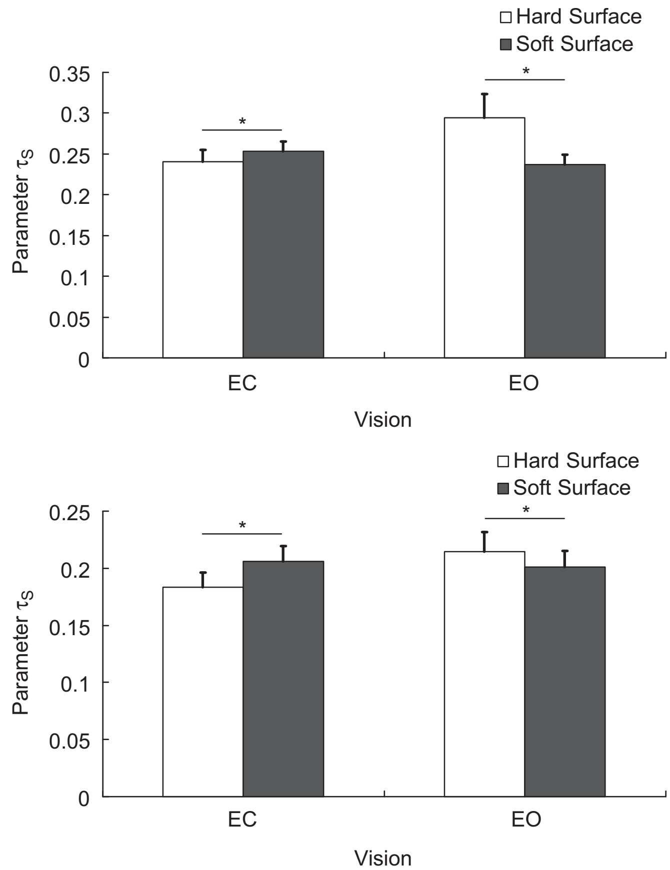

Fig. 3. Effects of vision and surface condition on local dynamic stability parameter τ_S (top, young; bottom, older). The effects of age and vision *x* surface were significant.

the surrogate data resulted in larger *A* values and smaller τ_S values within each age group and each sensory condition ($p<0.001$). Yet, there were no significant differences in B_S, B_L and τ_L, except that τ_L was significantly smaller for the surrogate data only in the ECSS condition for young individuals ($p<0.014$). Mean divergence curves for the surrogate data were shifted upward and diverged faster over a short timescale vs. those of the original data (except the one difference in τ_L noted). Thus, it could be concluded that fluctuations in COP time series are not due to a linearly auto-correlated Gaussian noise process.

3.2. Correlations among COP measures

Several significant correlations existed between the LDS parameters and either the scaling indices (α_{AP} and α_{ML}) or descriptive COP measures. However, these correlations were of relatively small magnitude ($r^2 \leqslant 0.29$; Table 2) for both the young and older individuals.

4. Discussion

Our hypothesis was that the LDS parameters, descriptive COP measures and a scaling index would each allow inferences on postural stability, but that there would not be a strong correlation between the LDS parameters and the other COP measures, the latter implying that LDS parameters indicate distinct aspects of postural control. LDS parameters were affected by age, vision and surface, comparable to the descriptive COP measures and the scaling index (Table 1). However, effects of age *x* vision and/or vision *x* surface interactions were inconsistent across some LDS parameters (A, B_L, τ_S and τ_L), descriptive COP measures (MV and EA95) and the scaling index. Correlation analysis also revealed that there were only weak correlations between the LDS parameters and the other COP measures ($r^2 \leqslant 0.25$ for the older and $r^2 \leqslant 0.29$ for the young). Thus, both aspects of the hypothesis were supported.

Interpretation of the stability parameters is focused here on A, τ_S and τ_L since the overall behavior of the exponential function (Eq. (3)) can be characterized by the COP excursion range in state space (A) and the divergence rates over short- and long-term timescales (τ_S and τ_L). Older individuals had a larger range of COP excursion than young individuals and altered somatosensory feedback generally caused an increase in A. Older individuals were relatively insensitive to eye closure effects on A (Fig. 2). In contrast, older individuals generally exhibited increased values of MV, EA95 and MPF_{AP} with eye closure, consistent with existing studies (e.g., Prieto et al., 1993). Age-related postural adaptations have been suggested to involve an increase in muscle activations and co-activations to stiffen the musculoskeletal system (Collins et al., 1995; Maki, 1993), and increased muscle activity was reported when visual feedback was removed (Benjuya et al., 2004). However, Laughton et al. (2003) noted that a casual relationship between increased muscle activity and increased postural sway is not clear. Given that the parameter A for older individuals was insensitive to vision, it would seem that older individuals successfully compensated for the removal of visual feedback with a stiffening strategy.

Older individuals exhibited faster rates of divergence (τ_S and τ_L) than young individuals (Figs. 2 and 3), which indicates that young individuals better regulated a local

Table 2
Coefficients of determination (r^2) between LDS parameters, scaling indices (α_{AP} and α_{ML}) and descriptive COP-based measures within each age group

	Older					Young				
	A	B_S	τ_S	B_L	τ_L	A	B_S	τ_S	B_L	τ_L
α_{AP}			0.10	0.14	0.18		−0.03	0.07	0.12	0.18
α_{ML}			0.25	0.10	0.04	0.04		0.15		
MV			−0.10	−0.07	−0.12	0.06	0.05	−0.04	−0.05	−0.29
EA95					−0.03					−0.04
MPF_{AP}	0.06		−0.06	−0.11	−0.22	0.14	0.04		−0.09	−0.25
MPF_{ML}	0.03		−0.12	−0.19	−0.15	0.03		−0.10	−0.07	−0.18

Only significant r^2 values are presented, and (−) indicates an inverse relationship.

perturbation. These age-related differences in τ may be explained by deteriorations in the neuromuscular system with age, such as decreased reflex rates (Chung et al., 2005), decreased tendon mechanical properties (Onambele et al., 2006) and a relative lack of precision of sensory sources (Horak and Macpherson, 1996; Woollacott, 2000). In turn, these changes are likely associated with differences in initial responses and a longer timescale for responses to local perturbations. Similarly, experimental modeling studies have demonstrated that a decrease in corrective torques to dampen a perturbation can increase sway over a short timescale (Peterka, 2000), and an increase in stiffness, damping and noise level can account for differences in sway data among older individuals (Maurer and Peterka, 2005). The stiffening strategy further supports a relative ineffectiveness of older individuals at suppressing local perturbations since increased muscle activity decreases force steadiness (De Luca et al., 1982; Galganski et al., 1993) and force steadiness declines with age (Laidlaw et al., 2000; Vaillancourt and Newell, 2003).

The LDS parameters had some significant correlations with the descriptive COP measures, yet the magnitude of these correlations was relatively small. Kang and Dingwell (2006) reported moderate–strong correlations among B_L, τ_S and both MV and COP range ($r^2 \geqslant 0.48$). Relatively weaker correlations were found here, possibly due to methodological differences between studies including a longer trial (5 min) with shoes worn, use of kinematic variables to compute the LDS parameters and a non-logarithmic mean divergence distance in the Kang and Dingwell study. Although there was no substantial correlation between the LDS parameter and α, the scaling index may still be related with postural control and stability in that the magnitudes of α_{AP} and α_{ML} indicated anti-persistent behavior of COP increments and the scaling behavior of COP was modulated by age and altered sensory conditions. Particularly, the magnitudes of α_{AP} ranged from 1.31 to 1.48 (ECSS = ECHS < EOHS < EOSS); correspondingly, from sub-diffusive fBm to Brownian motion (Delignières et al., 2005, 2006). COP time series in the AP direction behaved with stronger anti-persistence in COP increments when visual feedback was removed.

Some limitations of this study may limit generalization of the present findings. First, the duration of COP time series examined was relatively short (60 s). The results are thus not generalizable to more prolonged situations and/or conditions with fatigue. Second, the LDS parameters may be affected by measurement noise. Gaussian noise affects a mean-divergence curve over a short timescale, specifically by decreasing τ_S (Gao, 1997). However, the original COP data actually diverged more slowly over a short timescale than the surrogate data, which suggests that the results of LDS parameters were not significantly affected by measurement noise.

Despite these limitations, parameters describing LDS were directly extracted from the time-dependent behavior of COP time series in state space under the influence of small perturbations (i.e., during quiet upright stance). LDS results supported that older individuals use a stiffness strategy as age-related postural adaptation, in that older individuals exhibited faster divergence rates while the excursion range of COP in state space for older individuals was insensitive to vision. Further, there was no substantial correlation between the LDS parameters and other COP measures. Thus, the LDS parameters (A, τ_S and τ_L) provided a more detailed description of postural stability with age and altered sensory conditions, compared with the descriptive COP measures and the scaling index. Use of the LDS parameters appears to yield a distinct indication of postural control and stability, supplementing descriptive COP measures and the scaling index.

Conflict of interest

We declare that all authors have no financial or personal relationships with other persons or organizations that might inappropriately influence our work presented therein.

Acknowledgments

Partial support for this work was provided by Cooperative Agreement Number R01 OH04089 from the Centers for Disease Control and Prevention (CDC). Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the CDC.

References

Amoud, H., Abadi, M., Hewson, D.J., Michel-Pellegrino, V., Doussot, M., Duchêne, J., 2007. Fractal time series analysis of postural stability in elderly and control subjects. Journal of Neuroengineering and Rehabilitation 1, 4–12.

Baratto, L., Morasso, P.G., Re, C., Spada, G., 2002. A new look at posturographic analysis in the clinical context: sway-density versus other parameterization techniques. Motor Control 6 (3), 246–270.

Benjuya, N., Melzer, I., Kaplanski, J., 2004. Aging-induced shifts from a reliance on sensory input to muscle cocontraction during balanced standing. The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences. 59 (2), 166–171.

Burden, R.L., Faires, J.D., 1997. Numerical differentiation and integration. In: Numerical Analysis, sixth ed. Brooks Cole, Pacific Grove, CA (Chapter 4).

Chung, S.G., Van Rey, E.M., Bai, Z., Rogers, M.W., Roth, E.J., Zhang, L.Q., 2005. Aging-related neuromuscular changes characterized by tendon reflex system properties. Archives of Physical Medicine and Rehabilitation 86 (2), 318–327.

Collins, J.J., De Luca, C.J., Burrows, A., Lipsitz, L.A., 1995. Age-related changes in open-loop and closed-loop postural control mechanisms. Experimental Brain Research 104 (3), 480–492.

Delignières, D., Deschamps, T., Legros, A., Caillou, N., 2003. A methodological note on nonlinear time series analysis: is the open- and closed-loop model of Collins and De Luca (1993) a statistical artifact? Journal of Motor Behavior 35 (1), 86–97.

Delignières, D., Torre, K., Lemoine, L., 2005. Methodological issues in the application of monofractal analyses in psychological and

behavioral research. Nonlinear Dynamics, Psychology, and Life Sciences 9 (4), 435–461.
Delignières, D., Ramdani, S., Lemoine, L., Torre, K., Fortes, M., Ninot, G., 2006. Fractal analyses for 'short' time series: a re-assessment of classical methods. Journal of Mathematical Psychology 50, 525–544.
De Luca, C.J., LeFever, R.S., McCue, M.P., Xenakix, A.P., 1982. Control scheme governing concurrently active human motor units during voluntary contractions. Journal of Physiology 329, 129–142.
Du Pasquier, R.A., Blanc, Y., Sinnreich, M., Landis, T., Burkhard, P., Vingerhoets, F.J.G., 2003. The effect of aging on postural stability: a cross sectional and longitudinal study. Neurophysiologie Clinique 33 (5), 213–218.
Galganski, M.E., Fuglevand, A.J., Enoka, R.M., 1993. Reduced control of motor output in a human hand muscle of elderly subjects during submaximal contractions. Journal of Neurophysiology 69 (6), 2108–2115.
Gao, J., 1997. Recognizing randomness in a time series. Physica D 106, 49–56.
Hof, A.L., 1996. Scaling gait data to body size. Gait & Posture 4 (3), 222–223.
Horak, F.B., Macpherson, J.M., 1996. Postural orientation and equilibrium. In: Rowell, L.B., Shepherd, J.T. (Eds.), Handbook of Physiology. American Physiological Society, Washington, DC, pp. 255–292.
Kang, H.G., Dingwell, J.B., 2006. A direct comparison of local dynamic stability during unperturbed standing and walking. Experimental Brain Research 172 (1), 35–48.
Laidlaw, D.H., Bilodeau, M., Enoka, R.M., 2000. Steadiness is reduced and motor unit discharge is more variable in old adults. Muscle & Nerve 23 (4), 600–612.
Laughton, C.A., Slavin, M., Katdare, K., Nolan, L., Bean, J.F., Kerrigan, D.C., et al., 2003. Aging, muscle activity, and balance control: physiologic changes associated with balance impairment. Gait & Posture 18 (2), 101–108.
Maki, B.E., 1993. Biomechanical approach to quantifying anticipatory postural adjustments in the elderly. Medical & Biological Engineering & Computing 31 (4), 355–362.
Maurer, C., Peterka, R.J., 2005. A new interpretation of spontaneous sway measures based on a simple model of human postural control. Journal of Neurophysiology 93, 189–200.
Nies, N., Sinnott, P.L., 1991. Variations in balance and body sway in middle-aged adults. Subjects with healthy backs compared with subjects with low-back dysfunction. Spine 16 (3), 325–330.
Norris, J.A., Marsh, A.P., Smith, I.J., Kohut, R.I., Miller, M.E., 2005. Ability of static and statistical mechanics posturographic measures to distinguish between age and fall risk. Journal of Biomechanics 38 (6), 1263–1272.
Onambele, G.L., Narici, M.V., Maganaris, C.N., 2006. Calf muscle-tendon properties and postural balance in old age. Journal of Applied Physiology 100 (6), 2048–2056.
Pai, Y.C., Patton, J., 1996. Center of mass velocity-position predictions for balance control. Journal of Biomechanics 30 (4), 347–354.
Pascolo, P.B., Marini, A., Carniel, R., Barazza, F., 2005. Posture as a chaotic system and an application to the Parkinson's disease. Chaos, Solitons and Fractals 24 (5), 1343–1346.
Peterka, R.J., 2000. Postural control model interpretation of stabilogram diffusion analysis. Biological Cybernetics 82 (4), 335–343.
Prieto, T.E., Myklebust, J.B., Myklebust, B.M., 1993. Characterization and modeling of postural steadiness in the elderly: a review. IEEE Transactions on Rehabilitation Engineering 1 (1), 26–34.
Prieto, T.E., Myklebust, J.B., Hoffmann, R.G., Lovett, E.G., Myklebust, B.M., 1996. Measures of postural steadiness: differences between healthy young and elderly adults. IEEE Transactions on Biomedical Engineering 43 (9), 956–966.
Roerdink, M., De Haart, M., Daffertshofer, A., Donker, S.F., Geurts, A.C., Beek, P.J., 2006. Dynamical structure of center-of-pressure trajectories in patients recovering from stroke. Experimental Brain Research 174 (2), 256–269.
Rosenstein, M.T., Collins, J.J., De Luca, C.J., 1993. A practical method for calculating largest Lyapunov exponents from small data sets. Physica D 65 (1/2), 117–134.
Rosenstein, M.T., Collins, J.J., De Luca, C.J., 1994. Reconstruction expansion as a geometry-based framework for choosing proper delay times. Physica D 73 (1/2), 82–98.
Theiler, J., Eubank, S., Longtin, A., Galdrikian, B., Farmer, J.D., 1992. Testing for nonlinearity in time series: the method of surrogate data. Physica D 58 (1/4), 77–94.
Timmer, J., Häussler, S., Lauk, M., Lücking, C.-H., 2000. Pathological tremors: deterministic chaos or nonlinear stochastic oscillators? Chaos 10 (1), 278–288.
Vaillancourt, D.E., Newell, K.M., 2003. Aging and the time and frequency structure of force output variability. Journal of Applied Physiology 94 (3), 903–912.
Winter, D.A., 1995. (Anatomy, Biomechanics, Control) of Balance During Standing and Walking. Waterloo Biomechanics, Waterloo.
Woollacott, M.H., 2000. Systems contributing to balance disorders in older adults. The Journals of Gerontology. Series A, Biological Sciences and Medical Sciences 55 (8), M424–M428.

Interlibrary Loans and Journal Article Requests

Notice Warning Concerning Copyright Restrictions:

The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted materials.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One specified condition is that the photocopy or reproduction is not to be *"used for any purpose other than private study, scholarship, or research."* If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use," that user may be liable for copyright infringement.

Upon receipt of this reproduction of the publication you have requested, you understand that the publication may be protected by copyright law. You also understand that you are expected to comply with copyright law and to limit your use to one for private study, scholarship, or research and not to systematically reproduce or in any way make available multiple copies of the publication.

The Stephen B. Thacker CDC Library reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.

Terms and Conditions for items sent by e-mail:

The contents of the attached document may be protected by copyright law. The CDC copyright policy outlines the responsibilities and guidance related to the reproduction of copyrighted materials at CDC. If the document is protected by copyright law, the following restrictions apply:

- You may print only one paper copy, from which you may not make further copies, except as maybe allowed by law.
- You may not make further electronic copies or convert the file into any other format.
- You may not cut and paste or otherwise alter the text.