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# Physiological complexity and system adaptability: evidence from postural control dynamics of older adults

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**Manor B, Costa MD, Hu K, Newton E, Starobinets O, Kang HG, Peng CK, Novak V, Lipsitz LA.** Physiological complexity and system adaptability: evidence from postural control dynamics of older adults. *J Appl Physiol* 109: 1786–1791, 2010. First published October 14, 2010; doi:10.1152/japplphysiol.00390.2010.—The degree of multiscale complexity in human behavioral regulation, such as that required for postural control, appears to decrease with advanced aging or disease. To help delineate causes and functional consequences of complexity loss, we examined the effects of visual and somatosensory impairment on the complexity of postural sway during quiet standing and its relationship to postural adaptation to cognitive dual tasking. Participants of the MOBILIZE Boston Study were classified into mutually exclusive groups: controls [intact vision and foot somatosensation, $n = 299$, 76 ± 5 (SD) yr old], visual impairment only (<20/40 vision, $n = 81$, 77 ± 4 yr old), somatosensory impairment only (inability to perceive 5.07 monofilament on plantar halluxes, $n = 48$, 80 ± 5 yr old), and combined impairments ($n = 25$, 80 ± 4 yr old). Postural sway (i.e., center-of-pressure) dynamics were assessed during quiet standing and cognitive dual tasking, and a complexity index was quantified using multiscale entropy analysis. Postural sway speed and area, which did not correlate with complexity, were also computed. During quiet standing, the complexity index (mean ± SD) was highest in controls (9.5 ± 1.2) and successively lower in the visual (9.1 ± 1.1), somatosensory (8.6 ± 1.6), and combined (7.8 ± 1.3) impairment groups ($P = 0.001$). Dual tasking resulted in increased sway speed and area but reduced complexity ($P < 0.01$). Lower complexity during quiet standing correlated with greater absolute ($R = -0.34$, $P = 0.002$) and percent ($R = -0.45$, $P < 0.001$) increases in postural sway speed from quiet standing to dual-tasking conditions. Sensory impairments contributed to decreased postural sway complexity, which reflected reduced adaptive capacity of the postural control system. Relatively low baseline complexity may, therefore, indicate control systems that are more vulnerable to cognitive and other stressors.

posture; vision; somatosensation; dual tasking

THE DYNAMICS OF VARIOUS HUMAN physiological processes are inherently complex (31). "Complexity," in this sense, refers to the presence of nonrandom fluctuations on multiple time scales in the seemingly irregular dynamics of physiological outputs (9, 29). Mounting evidence indicates that biological aging and/or disease are often associated with a reduction in physiological complexity. Such reductions, which have been observed in the dynamics of heart rate (6), respiration (32), gait (11, 16), posture (10, 12), motor activity (22), and red blood cell "flickering" (8), may be associated with aging and adverse clinical outcomes (6, 10, 16). Despite evidence of its potential importance to biology, physiological complexity is an emerging field, and, as yet, there are no compelling models of complexity regulation for any physiological system. Moreover, the causes and functional implications of reduced physiological complexity are largely unexplored.

The postural control system consists of somatosensory, visual, and vestibular sensory feedback networks, numerous brain regions, and the musculoskeletal system (19, 40). This system regulates the body's postural sway with respect to its base of support, thereby enabling upright stance and the capacity to adapt to stressors in unpredictably changing environments. Similar to other physiological signals, the postural sway dynamics of quiet, upright standing are complex; i.e., they contain correlated fluctuations over multiple time scales (10, 12, 24, 38). The effects of aging on postural sway complexity are debated (10, 12). Our initial analysis of the MOBILIZE Boston Study (24) indicated that postural sway dynamics during quiet standing, as computed by the multiscale entropy (MSE) method, were less complex in prefrail and frail than nonfrail older adults. Moreover, superimposition of a cognitive dual task further lowered the complexity of postural sway motions during standing.

Physiological complexity is believed to arise from the underlying networks of nonlinear interactions among multiple control nodes that regulate system behavior over multiple scales of time (20, 29). Therefore, despite limited empirical evidence, measures of physiological complexity have been theorized to relate to system functionality as defined by the capacity to generate adaptive responses to stressors (14, 28). In the present study, we conducted further analyses of the MOBILIZE Boston Study to test the following hypotheses: *1*) sensory impairments important to postural sway control are associated with relatively low physiological complexity in standing postural sway dynamics, and *2*) a functional consequence of low physiological complexity is a reduced capacity of the system to adapt to stress.

To test these hypotheses, we studied the effect of chronic sensory impairment on postural sway complexity during quiet standing and its relationship to postural adaptation to a cognitive dual task. Specifically, we examined the influence of reduced visual acuity and/or lower-extremity somatosensation, as each decreases feedback to the postural control system (15, 18). We anticipated that *1*) postural sway complexity during quiet standing would be lower in older adults with visual and/or somatosensory impairments than controls and *2*) across all subjects, the degree of complexity associated with quiet

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standing would inversely correlate with the change in sway during dual tasking.

## METHODS

*Participants and procedures.* Baseline data collected from 765 participants in the MOBILIZE Boston Study (24, 27) were further analyzed. This prospective study examines risk factors for falls in community-dwelling adults ≥70 yr old. Participants provided informed consent as approved by the Hebrew SeniorLife Institutional Review Board, represented local demographic distributions, and were recruited from defined census tracks in the Boston area. MOBILIZE Boston Study exclusion criteria were as follows: *1*) terminal disease, *2*) cognitive impairment [Mini-Mental State Exam (13) score <18], *3*) inability to walk 20 m without personal assistance, and *4*) inability to understand English. For the present analysis, participants with Parkinson's disease ($n = 9$) and history of stroke ($n = 33$) were also excluded.

Eligible subjects were retrospectively classified into four mutually exclusive groups according to visual acuity and foot sole somatosensory status: *1*) controls (i.e., neither impairment), *2*) visual impairment only, *3*) somatosensory impairment only, and *4*) combined impairments. Visual acuity was assessed with the Good-Lite LD-10 chart in a Good-Lite model 600A light box using standard procedures. Participants were allowed to wear prescribed corrective lenses. Performance was scored from 1 to 100 (Snellen chart equivalents of 20/123 and 20/13 vision). Visual impairment was defined as a Good-Lite score <50 (<20/40 vision) (39). Foot sole somatosensation was assessed on the skin of the right and left non-weight-bearing halluxes using a 5.07 monofilament (North Coast Medical) and a forced-choice method. Four trials were performed on each side. Somatosensory impairment was defined as fewer than three correct responses for either foot.

*Assessment of standing postural control.* Postural control was assessed while participants stood barefoot on a force platform (model 9286AA, Kistler Instrument, Amherst, NY) with feet shoulder-width apart and eyes open. Participants were allowed to wear prescribed corrective lenses. Chalk outlines of the feet were drawn to ensure consistent intertrial foot placement. Each subject performed five, 30-s trials under two conditions: quiet standing and cognitive dual tasking (see below). Trials were grouped by sets of five to minimize possible carryover effects between conditions (24). One minute of seated rest was given between trials, and set order was randomized between participants.

The cognitive task consisted of verbalized serial subtractions. Each subject counted backwards by 3 from 500 throughout the trial. In each subsequent trial, participants began subtracting from the final number verbalized in the previous trial. The number of errors was recorded by the investigator. If participants made five or more errors in a single trial, the test was modified to counting backwards by one from 500. For the present analysis, the potential confounder of differing cognitive dual task difficulty as a result of performing different cognitive tasks (41) was reduced by including only participants that completed the original dual task ($n = 453$).

*Analysis of standing postural sway dynamics.* Postural sway [i.e., center-of-pressure (COP)] time series were derived from force platform measurements at a sampling frequency of 240 Hz. MSE analysis (9, 24) was completed on each anteroposterior time series[1] using MATLAB 7.04 (Mathworks, Natick, MA) and averaged separately across quiet-standing and dual-tasking trials. MSE analysis quantifies the degree of irregularity in the fluctuations of a time series over multiple time scales (9). As this analysis requires multiple repetitions of a given dynamical pattern, relatively low-frequency (<7.5 Hz) components of the COP time series were first filtered using empirical mode decomposition (23). Thus, dynamics were only examined over time scales <133 ms (9). Filtered time series were then "coarse-grained" to derive multiple time series, each capturing system dynamics on a given time scale. Briefly, the coarse-grained time series for scale factor $n$ is the sequence of mean COP values produced by dividing the original time series into nonoverlapping windows with $n$ data points and then calculating the mean value for each window. According to Kang et al. (24), each time series was coarse-grained into scales 2–8. The sample entropy of each coarse-grained time series was then calculated to determine the degree of irregularity associated with each time scale (i.e., greater entropy is associated with greater irregularity) (35). Finally, a "complexity index" (24) was computed by plotting the sample entropy of each coarse-grained time series as a function of time scale and then calculating the area under the given curve. As such, relatively high complexity indexes indicate greater multiscale irregularity.

Traditional measures of postural sway were also calculated from unfiltered time series. Variables included postural sway speed (i.e., COP path length divided by trial duration) and area (i.e., the area of a confidence ellipse enclosing 95% of the COP signal). Our previous study indicated that these traditional measures do not correlate with the complexity index (24). Analysis of the current data set confirmed a lack of correlation across all parameters ($r^2 = 0.005–0.017$) and, furthermore, indicated that each of these variables loaded on independent principal components (Table 1). Specifically, the COP area associated with eyes-open and eyes-closed standing loaded primarily on *components 1–2*, eyes-open and eyes-closed COP velocity loaded primarily on *components 3–4*, and eyes-open and eyes-closed COP complexity loaded primarily on *components 5–6*. These observations provide evidence that each of the included measures reflects a fundamentally different property of postural sway.

*Assessment of cognitive and physical function.* Participants also completed several relevant tests of cognitive and physical function. Executive function was assessed by the time taken to complete trail-making test part B (36). Clinical balance was assessed by the Berg balance scale (4), which rates performance on 14 functional mobility items using a 5-point ordinal scale (0 = lowest performance, 56 = highest performance). Self-reported 1-yr history of falls was also recorded.

*Statistical analysis.* Analyses were performed using SAS 9.1 software (SAS Institute, Cary NC). Descriptive statistics were used to summarize all variables. One-way ANOVA or Kruskal-Wallis tests were used to examine demographics, cognitive function, and clinical balance across groups. To examine the effect of sensory impairment on postural sway, repeated-measures analyses of covariance were completed on each sway variable with group (i.e., controls, visual, somatosensory, combined impairment) and condition (i.e., quiet standing, dual tasking) as between- and within-group factors, respec-

Table 1. *Principal components analysis of postural sway parameters*

| | Principal Component Loadings* | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Quiet standing | | | | | | |
| Complexity | | | | | −0.59 | 0.80 |
| Speed | | | −0.26 | 0.96 | | |
| Area | −0.40 | −0.91 | | | | |
| Dual tasking | | | | | | |
| Complexity | | | | | −0.80 | −0.60 |
| Speed | | | −0.96 | −0.26 | | |
| Area | −0.92 | 0.40 | | | | |

*Loadings <0.1 are not shown.

[1] Signal-to-noise ratio of the force plate in our laboratory was previously determined for a representative examination (24). Across the bandwidth of interest, signal-to-noise ratios in anteroposterior and mediolateral directions were >10 and <1, respectively. For this reason, the complexity index was computed only from anteroposterior postural sway dynamics.

Table 2. *Group characteristics*

| | Group | | | | |
|---|---|---|---|---|---|
| | Controls | Visual impairment | Somatosensory impairment | Combined impairment | *P* Value |
| Sample size | 299 | 81 | 48 | 25 | |
| Female, % | 59 | 60 | 60 | 52 | 0.18 |
| Age, yr | 76 ± 5* | 77 ± 4*† | 80 ± 5† | 80 ± 4† | **<0.001** |
| Height, cm | 165 ± 10 | 162 ± 9 | 168 ± 8 | 169 ± 10 | 0.11 |
| Body mass, kg | 75 ± 15 | 73 ± 13 | 77 ± 16 | 77 ± 16 | 0.16 |
| Vision (Good-Lite score) | 73 ± 8† | 44 ± 5* | 69 ± 5† | 45 ± 5* | **<0.001** |
| Vision (Snellen equivalent) | 20/24 | 20/46 | 20/25 | 20/45 | |
| Trail-making test part B, s | 112 ± 61* | 144 ± 80† | 115 ± 37* | 147 ± 81† | **0.001** |
| Berg balance scale | 51 ± 5* | 49 ± 5*† | 47 ± 5† | 46 ± 7† | **0.001** |
| %Fallers (3-mo history) | 27* | 32*† | 41† | 48† | **0.009** |
| %Diabetes | 14 | 15 | 18 | 19 | 0.63 |
| %Hypertensive | 8 | 8 | 12 | 16 | 0.09 |

Values are means ± SD. *P* values are from ANOVA. Bold font represents significance at ≤0.01 (adjusted for multiple comparisons). Within each row, group means with different symbols (*, †) are significantly different from one another based on Tukey's post hoc testing of adjusted models.

tively. Age, sex, height, body mass, and cognitive function (i.e., trail-making test part B score) were included as covariates to control for potential confounding effects of group differences in these variables. Tukey's post hoc testing was used where needed. Pearson's product correlations were then computed to determine the relationships between the complexity index during quiet standing and the change in sway during dual tasking, as calculated by the absolute and percent change in postural sway speed and area from quiet-standing to dual-tasking conditions. Regression analyses were also employed to examine these relationships while adjusting for the aforementioned covariates. To control overall type I error rate, a Sidak correction for multiple comparisons adjusted for high correlation between postural sway summary statistics was used ($P < 0.01$) (26).

## RESULTS

*Group characteristics.* Table 2 shows group differences in demographic characteristics, cognitive function, and clinical balance. The somatosensory and combined impairment groups were older than controls. The extent of visual impairment was similar between the visual and combined impairment groups, and these groups performed worse on the trail-making test than controls and the somatosensory impairment group. The somatosensory and combined impairment groups had significantly worse Berg balance scores and were more likely to have suffered a fall in the previous year than controls. The prevalence of diabetes and hypertension was not different between groups.

*Effect of sensory impairment on postural sway complexity.* Figure 1 illustrates the MSE curves created by plotting the sample entropy (mean ± SE) of postural sway displacements as a function of time scale. The complexity index, which reflects the area under the MSE curve, differed by group ($F_{3,453} = 4.3$, $P = 0.005$; Fig. 2). Post hoc testing revealed that the complexity index was greatest in controls and successively smaller in the visual, somatosensory, and combined impairment groups (all differences were significant). Similar group differences were also observed in the complexity index taken from quiet-standing trials only. Across all groups, cognitive dual tasking decreased the complexity index ($F_{1,453} = 3.4$, $P < 0.009$). No group-by-condition interaction was observed.

*Effect of sensory impairment on traditional sway parameters.* Postural sway speed ($F_{3,453} = 4.9$, $P = 0.002$) and area ($F_{3,453} = 5.9$, $P < 0.001$) differed by group (Fig. 2). Postural sway speed was fastest in the combined impairment group, slower in the somatosensory impairment group, and slowest in the visual impairment and control groups. Postural sway area was greater in the combined impairment group than the other three groups, which did not differ from one another.

With all groups combined, dual tasking resulted in faster postural sway speed ($F_{1,453} = 2.96$, $P = 0.01$) and area ($F_{1,453} = 2.88$, $P = 0.01$).

The impact of dual tasking on postural sway speed differed by group ($F_{3,453} = 4.8$, $P = 0.002$; Fig. 2). Specifically, dual tasking induced significantly greater increases in postural sway speed within the combined and somatosensory impairment groups than the visual impairment and control groups. No group-by-condition interaction was observed for postural sway area.

*Relationship between baseline complexity and postural adaptation to dual tasking.* With all participants combined, the complexity index obtained from quiet standing correlated with percent increases in postural sway speed from quiet-standing to dual-tasking conditions ($R = -0.45$, $P < 0.001$; Fig. 3). Regression analysis revealed that this correlation remained significant ($R = -0.40$, $P = 0.009$) after adjustment for the covariates of group, age, sex, height, body mass, and trail-

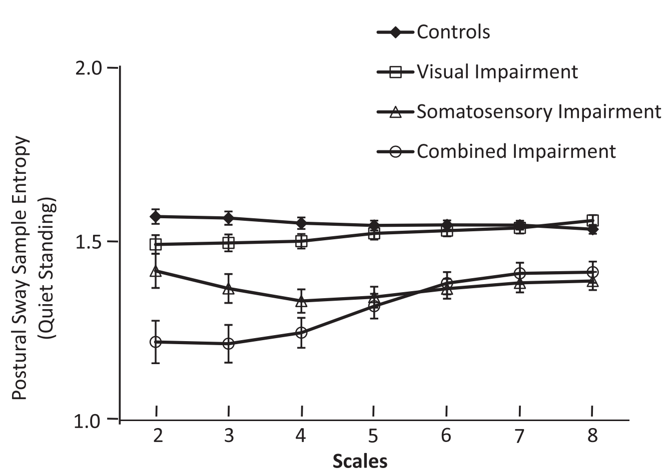


Fig. 1. Multiscale entropy (MSE) analysis of postural sway dynamics. MSE curve, created by plotting sample entropy (mean ± SE) of postural sway (i.e., center-of-pressure) displacements as a function of time scale, is shown for each group. Complexity index was determined by computing the area under the MSE curve for each trial.

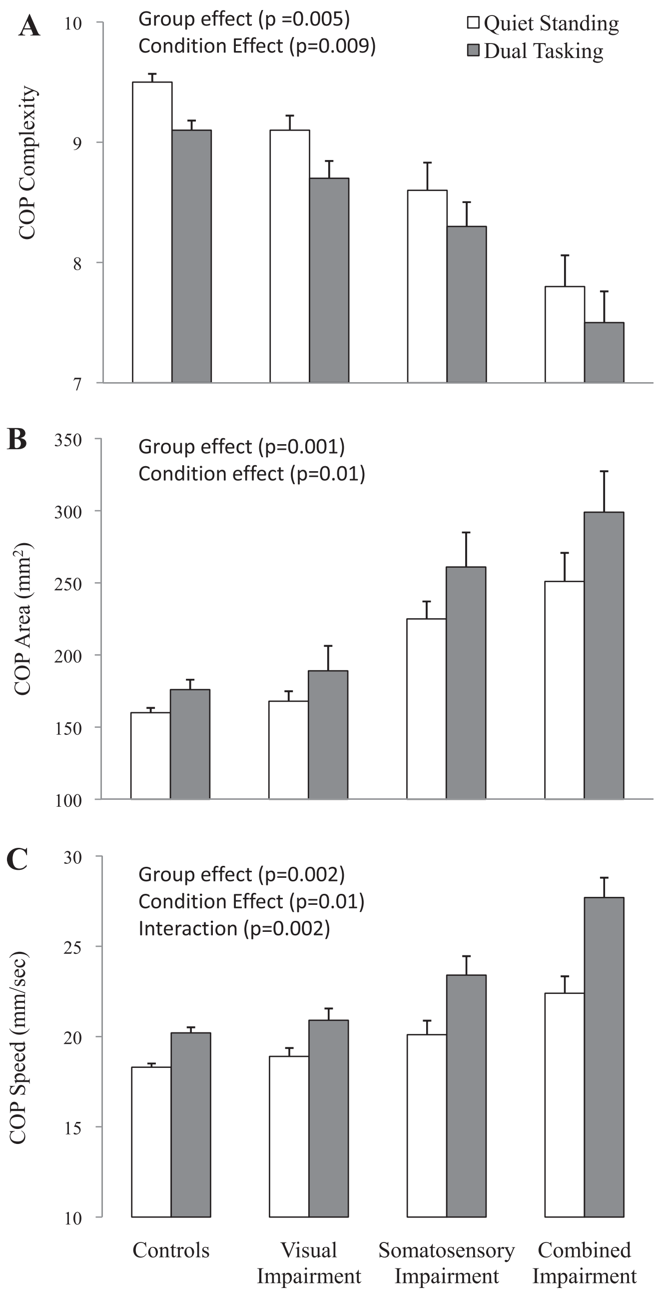


Fig. 2. Effects of sensory impairment and cognitive dual tasking on postural sway [center-of-pressure (COP)] dynamics. Postural sway complexity (*A*), area (*B*), and speed (*C*) are shown during quiet-standing and dual-tasking conditions. Complexity index was greatest in controls and successively smaller in visual, somatosensory, and combined impairment groups. In general, somatosensory and/or combined impairment groups exhibited greater sway speed and area than visual impairment and control groups. Dual tasking reduced complexity yet increased postural sway speed and area. Dual tasking led to greater increases in sway speed within combined and somatosensory impairment groups than visual impairment and control groups. Values are group means ± SE.

making test part B score. Similar relationships were observed between the complexity index and absolute changes in sway speed induced by dual tasking in unadjusted ($R = -0.34$, $P = 0.002$) and adjusted ($R = -0.30$, $P = 0.01$) models. Trends were present between the complexity index during quiet standing and the change in postural sway area during the dual task in unadjusted ($P = 0.08–0.09$) and adjusted ($P = 0.12–0.13$) models.

## DISCUSSION

In this study, we observed that chronic sensory impairments were associated with lower physiological complexity of the postural sway dynamics during quiet standing. Postural sway complexity was highest in controls, lower in those with poor visual acuity, and lower still in those with impaired foot sole sensation. Individuals with concomitant deterioration of both sensory modalities exhibited the lowest complexity index values. Cognitive dual tasking decreased the complexity, yet increased the speed and area, of postural sway dynamics. Moreover, dual tasking had a greater impact on postural sway speed in those with somatosensory impairment than those with visual impairment and controls.

Across all subjects, the degree of postural sway complexity was associated with the adaptive capacity of the postural control system; i.e., those with lower postural sway complexity during quiet standing exhibited greater absolute and percent increases in postural sway speed from quiet-standing to dual-tasking conditions. These observations of the human postural control system support evidence of complex, multiscale control within a physiological system. Moreover, they suggest that impaired feedback control relates to low physiological complexity, which may serve as a noninvasive marker of diminished functionality as defined by a reduced adaptive capacity of the system.

*Complexity of quiet-standing postural sway dynamics.* Mathematical models of physical systems suggest that complex patterns require multiscale organization, where networks of feedback interactions among control nodes influence behavior across multiple scales of time and/or space (2, 3). In the present study, we observed that the degree of complexity associated with postural control system behavior was correlated with the integrity of involved sensory systems. The further observation that impairment to a single feedback system (i.e., visual or somatosensory) affected behavior over multiple time scales provides strong evidence of complex, multiscale organization within the human postural control system. Previous reports

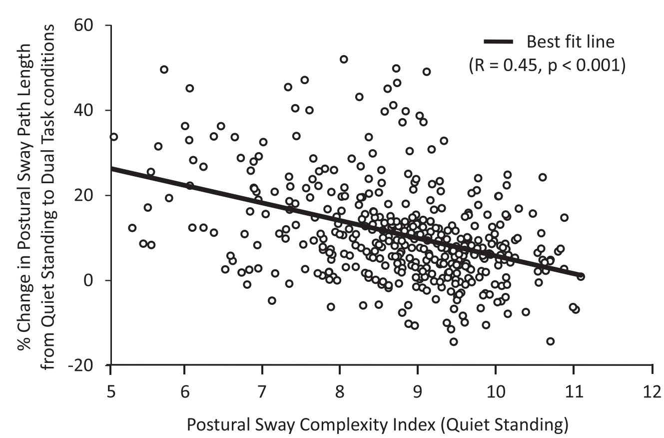


Fig. 3. Relationship between postural sway complexity and the impact of cognitive dual tasking. For all participants, lower postural sway complexity index values during quiet standing were associated with greater percent and absolute (not shown) increases in sway speed from quiet-standing to dual-tasking conditions.

also point to such complex control with respect to the cardiovascular system. For example, animal studies have demonstrated that ablation of the suprachiasmatic nucleus, a small area of the central nervous system responsible for the generation of 24-h circadian rhythms, abolished the multiscale complexity of heart rate fluctuations over multiple time scales ranging from minutes to hours (21). Human studies have also demonstrated that pharmacological blockade of vagal nerve outflow (33) and chronic autonomic nervous system dysfunction (1) lead to reduced complexity as measured by the degree of long-range correlation in heart rate dynamics over time. Taken together, these previous observations and our present findings suggest that integrative, systems-based approaches are needed to obtain a network view of balance system components and their interactions to model and measure their dynamics in experimental and clinical settings.

The exact physiological pathways through which the examined sensory impairments associated with multiscale alterations in postural control are unknown. During upright stance, postural sway is known to be regulated by the active and/or passive generation of body-stabilizing torque. Active mechanisms include joint stiffness regulation via modulation of muscular tone, mono- and polysynaptic reflex arcs, and/or volitional movements (7, 19). Here, it is important to note that because of the length of available postural sway time series, we only examined the effect of fluctuations over relatively short time scales (i.e., 8–33 ms) on sample entropy and, thus, physiological complexity. Visual and somatosensory impairments were associated with altered regularity of postural sway fluctuations at frequencies higher than those influenced by short-latency monosynaptic reflex loops observed during weight-bearing conditions (37). It may therefore be postulated that such changes arose from alterations in joint stiffness through unique patterns of nonreflexive muscular tone and/or cocontraction across the hips and lower-extremity joints. Future research examining postural sway complexity, along with simultaneous acquisition of lower-extremity muscular activity, may therefore offer a unique opportunity to elucidate the multiscale contribution of specific sources of sensory feedback in the control of standing posture in health and disease.

*Postural adaptation to a cognitive dual task.* In general, the multiscale organization that characterizes a complex control system increases the functionality of that system; i.e., it affords the capacity to successfully adapt to the innumerable types of internal and external perturbations encountered throughout daily life. Previous studies on physiological systems have reported evidence in support of this theory. For example, breakdown in the complex fractal scaling of heart rate fluctuations predicts survival rate in patients with acute myocardial infarction (5), heart failure (17), and stroke (30). Our observations of the human postural control system, including those from our initial analysis of the MOBILIZE Boston Study data set, indicate less postural sway complexity in frail (24) and fall-prone (10) populations than age-matched controls.

The present study has extended these previous observations by providing a link between the baseline complexity of a physiological system and its ability to adapt to an experimentally induced perturbation. We observed that the degree of postural sway complexity associated with quiet standing was inversely correlated with postural adaptation to cognitive dual tasking. The significant correlation between baseline complexity and the dual task impact on postural sway speed, in particular, is nontrivial, as feedback related to this variable appears to be of critical importance to the control of postural sway (25, 34).

As complexity was only computed from anteroposterior sway dynamics, elucidation of the relationship between mediolateral sway complexity and the impact of dual tasking is needed. Moreover, as cognitive dual tasking is only one type of perturbation, research is also warranted to further validate the relationship between baseline complexity of the postural control system (as well as other physiological systems) and their capacity to adapt to multiple types of internal and external stressors across multiple time scales. Nevertheless, the present observations provide evidence that low physiological complexity may indicate a relatively simple control system that is less adaptive to perturbation and, thus, more vulnerable to the stressors of everyday life.

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## DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

## REFERENCES

1. **Aoyagi N, Struzik ZR, Kiyono K, Yamamoto Y.** Autonomic imbalance induced breakdown of long-range dependence in healthy heart rate. *Methods Inf Med* 46: 174–178, 2007.
2. **Bak P, Tang C, Wiesenfeld K.** Self-organized criticality: an explanation of the 1/*f* noise. *Phys Rev Lett* 59: 381–384, 1987.
3. **Basu S, Foufoula-Georgiou E, Porte-Agel F.** Synthetic turbulence, fractal interpolation, and large-eddy simulation. *Phys Rev E Stat Nonlin Soft Matter Phys* 70: 026310, 2004.
4. **Berg KO, Wood-Dauphinee SL, Williams JI, Maki B.** Measuring balance in the elderly: validation of an instrument. *Can J Public Health* 83: S7–S11, 1992.
5. **Bigger JT Jr, Steinman RC, Rolnitzky LM, Fleiss JL, Albrecht P, Cohen RJ.** Power law behavior of RR-interval variability in healthy middle-aged persons, patients with recent acute myocardial infarction, and patients with heart transplants. *Circulation* 93: 2142–2151, 1996.
6. **Chaves PH, Varadhan R, Lipsitz LA, Stein PK, Windham BG, Tian J, Fleisher LA, Guralnik JM, Fried LP.** Physiological complexity underlying heart rate dynamics and frailty status in community-dwelling older women. *J Am Geriatr Soc* 56: 1698–1703, 2008.
7. **Collins JJ, De Luca CJ.** The effects of visual input on open-loop and closed-loop postural control mechanisms. *Exp Brain Res* 103: 151–163, 1995.
8. **Costa M, Ghiran I, Peng CK, Nicholson-Weller A, Goldberger AL.** Complex dynamics of human red blood cell flickering: alterations with in vivo aging. *Phys Rev E Stat Nonlin Soft Matter Phys* 78: 020901, 2008.
9. **Costa M, Goldberger AL, Peng CK.** Multiscale entropy analysis of complex physiologic time series. *Phys Rev Lett* 89: 068102, 2002.
10. **Costa M, Priplata AA, Lipsitz LA, Wu Z, Huang NE, Goldberger AL, Peng CK.** Noise and poise: enhancement of postural complexity in the elderly with a stochastic-resonance-based therapy. *Europhys Lett* 77: 68008, 2007.
11. **Delignieres D, Torre K.** Fractal dynamics of human gait: a reassessment of the 1996 data of Hausdorff et al. *J Appl Physiol* 106: 1272–1279, 2009.
12. **Duarte M, Sternad D.** Complexity of human postural control in young and older adults during prolonged standing. *Exp Brain Res* 191: 265–276, 2008.

13. **Folstein MF, Robins LN, Helzer JE.** The Mini-Mental State Examination. *Arch Gen Psychiatry* 40: 812, 1983.
14. **Goldberger AL, Amaral LA, Hausdorff JM, Ivanov PC, Peng CK, Stanley HE.** Fractal dynamics in physiology: alterations with disease and aging. *Proc Natl Acad Sci USA* 99: 2466–2472, 2002.
15. **Haibach P, Slobounov S, Newell K.** Egomotion and vection in young and elderly adults. *Gerontology* 55: 637–643, 2009.
16. **Hausdorff JM, Rios DA, Edelberg HK.** Gait variability and fall risk in community-living older adults: a 1-year prospective study. *Arch Phys Med Rehabil* 82: 1050–1056, 2001.
17. **Ho KK, Moody GB, Peng CK, Mietus JE, Larson MG, Levy D, Goldberger AL.** Predicting survival in heart failure case and control subjects by use of fully automated methods for deriving nonlinear and conventional indices of heart rate dynamics. *Circulation* 96: 842–848, 1997.
18. **Horak FB, Dickstein R, Peterka RJ.** Diabetic neuropathy and surface sway-referencing disrupt somatosensory information for postural stability in stance. *Somatosens Mot Res* 19: 316–326, 2002.
19. **Horak F, MacPherson JM.** Postural orientation and equilibrium. In: *Handbook of Physiology. Exercise: Regulation and Integration of Multiple Systems.* Bethesda, MD: Am. Physiol. Soc., 1996, sect. 12, p. 255–292.
20. **Hu K, Ivanov PC, Chen Z, Hilton MF, Stanley HE, Shea SA.** Nonrandom fluctuations and multi-scale dynamics regulation of human activity. *Physica A* 337: 307–318, 2004.
21. **Hu K, Scheer FA, Buijs RM, Shea SA.** The endogenous circadian pacemaker imparts a scale-invariant pattern of heart rate fluctuations across time scales spanning minutes to 24 hours. *J Biol Rhythms* 23: 265–273, 2008.
22. **Hu K, Van Someren EJ, Shea SA, Scheer FA.** Reduction of scale invariance of activity fluctuations with aging and Alzheimer's disease: involvement of the circadian pacemaker. *Proc Natl Acad Sci USA* 106: 2490–2494, 2009.
23. **Huang NE, Shen Z, Long SR, Wu MC, Shih HH, Zheng Q, Yen NC, Tung CC, Liu HH.** The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. *Proc R Soc Lond* 454: 903–995, 1998.
24. **Kang HG, Costa MD, Priplata AA, Starobinets OV, Goldberger AL, Peng CK, Kiely DK, Cupples LA, Lipsitz LA.** Frailty and the degradation of complex balance dynamics during a dual-task protocol. *J Gerontol A Biol Sci Med Sci* 64: 1304–1311, 2009.
25. **Kiemel T, Oie KS, Jeka JJ.** Multisensory fusion and the stochastic structure of postural sway. *Biol Cybern* 87: 262–277, 2002.
26. **Leon AC, Heo M.** A comparison of multiplicity adjustment strategies for correlated binary endpoints. *J Biopharm Stat* 15: 839–855, 2005.
27. **Leveille SG, Kiel DP, Jones RN, Roman A, Hannan MT, Sorond FA, Kang HG, Samelson EJ, Gagnon M, Freeman M, Lipsitz LA.** The MOBILIZE Boston Study: design and methods of a prospective cohort study of novel risk factors for falls in an older population. *BMC Geriatr* 8: 16, 2008.
28. **Lipsitz LA.** Dynamics of stability: the physiologic basis of functional health and frailty. *J Gerontol A Biol Sci Med Sci* 57: B115–B125, 2002.
29. **Lipsitz LA, Goldberger AL.** Loss of "complexity" aging. Potential applications of fractals and chaos theory to senescence. *JAMA* 267: 1806–1809, 1992.
30. **Makikallio AM, Makikallio TH, Korpelainen JT, Sotaniemi KA, Huikuri HV, Myllyla VV.** Heart rate dynamics predict poststroke mortality. *Neurology* 62: 1822–1826, 2004.
31. **Peng CK, Costa M, Goldberger AL.** Adaptive data analysis of complexity fluctuations in physiologic time series. *Adv Adapt Data Anal* 1: 61–70, 2009.
32. **Peng CK, Mietus JE, Liu Y, Lee C, Hausdorff JM, Stanley HE, Goldberger AL, Lipsitz LA.** Quantifying fractal dynamics of human respiration: age and gender effects. *Ann Biomed Eng* 30: 683–692, 2002.
33. **Penttila J, Helminen A, Jartti T, Kuusela T, Huikuri HV, Tulppo MP, Scheinin H.** Effect of cardiac vagal outflow on complexity and fractal correlation properties of heart rate dynamics. *Auton Autacoid Pharmacol* 23: 173–179, 2003.
34. **Peterka RJ.** Sensorimotor integration in human postural control. *J Neurophysiol* 88: 1097–1118, 2002.
35. **Pincus SM.** Approximate entropy as a measure of system complexity. *Proc Natl Acad Sci USA* 88: 2297–2301, 1991.
36. **Reitan RM, Wolfson D.** *The Halstead-Reitan Neuropsychological Test Battery: Theory and Clinical Interpretation.* Tucson, AZ: Neuropsychology Press, 1993.
37. **Schillings AM, Van Wezel BM, Mulder T, Duysens J.** Widespread short-latency stretch reflexes and their modulation during stumbling over obstacles. *Brain Res* 816: 480–486, 1999.
38. **Thurner S, Mittermaier C, Ehrenberger K.** Change of complexity patterns in human posture during aging. *Audiol Neurootol* 7: 240–248, 2002.
39. **West SK, Munoz B, Rubin GS, Schein OD, Bandeen-Roche K, Zeger S, German S, Fried LP.** Function and visual impairment in a population-based study of older adults. The SEE project Salisbury Eye Evaluation. *Invest Ophthalmol Vis Sci* 38: 72–82, 1997.
40. **Winter DA, Patla AE, Frank JS.** Assessment of balance control in humans. *Med Prog Technol* 16: 31–51, 1990.
41. **Woollacott M, Vander VT.** Non-visual spatial tasks reveal increased interactions with stance postural control. *Brain Res* 1208: 95–102, 2008.