Sensitivity and Reliability of Local Dynamic Stability: Effects of Age and Altered Sensory Conditions

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Sensitivity and reliability of local dynamic stability: effects of age and altered sensory conditions

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Local dynamic stability was investigated during quiet upright stance with respect to age and altered sensory conditions. From center of pressure (COP) trajectories, the largest Lyapunov exponent (λ_{max}) was extracted to directly parameterize local dynamic stability, and the reliability of λ_{max} was assessed using the intra-class correlation coefficient (ICC). Thirty two participants volunteered for upright quiet stance trials. Vision and somatosenstaion were experimentally altered: vision was modified by eye closure, and somatosensation by using both a hard surface (HS) and a soft surface (SS). Age and vision had main effects on λ_{ma}, and the age x vision and vision x surface interaction effects were also significant. In general, older participants were less stable (i.e., higher λ_{max}) than younger, and altered sensory information resulted in a decrease in stability. Reliability was higher for older versus younger participants. Use of λ_{max} enabled a direct assessment of age-related differences in local dynamic stability and effects of altered sensory conditions. Such non-linear measures can provide additional information to that available from traditional COP-based analyses.

INTRODUCTION

A decline in postural control system performance has been associated with an increased probability of a fall (Redfern et al., 1997; Browne et al., 2002). Postural control strategies in quiet upright stance are reflected in the center of pressure (COP) dynamics (Prieto et al., 1993; Winter, 1995). Postural steadiness and stability are often inferred from systematic changes in descriptive COP-based measures (e.g., mean velocity, ellipse area, etc.) under diverse conditions such as aging, pathology and altered sensory input (e.g., Prieto et al., 1993; Baratto et al., 2002). However, descriptive COP-based measures may not sufficiently reflect dynamic characteristics of COP such as stability.

Nonlinear time-series analyses (along with the descriptive COP-based measures) are increasingly being used to investigate the dynamic characteristics of COP trajectories (Kang & Dingwell, 2006; Roerdink et al., 2006). In particular, local dynamic stability (LDS) was quantified using the largest Lyapunov exponent (λ_{max}) to assess improvements of stroke patients' postural control during rehabilitation (Roerdink et al., 2006). Dynamic stability properties of walking and standing were also directly compared and found not correlated, using a time-dependent behavior of trunk kinematic variables in state space (Kang & Dingwell, 2006).

However, the sensitivity of λ_{max} has not yet been fully investigated using COP trajectories under varied conditions, nor has the reliability of LDS measures been systematically evaluated. The objective of the present study was to determine the sensitivity and reliability of LDS measures with respect to different age groups and altered sensory conditions, using a time-dependent behavior of COP time series in state space. The potential of λ_{max} was thereby examined, as a tool to directly assess performance of the postural control system.

METHODS

Thirty two healthy individuals (16 younger and 16 older, gender balanced in each group) from the university and local community volunteered for the study, and completed an informed consent procedure approved by the Virginia Tech Institutional Review Board. The mean(sd) age, stature and body mass were 20.9(1.7) yr, 171.1(6.8) cm and 67.3(12) kg for younger 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.

Experimental procedures

Trials were conducted with three replications of four sensory conditions. The order of the 12 total trials was fully randomized, with at least one minute of rest between each. Visual conditions were eyes-open (EO) and eyes-closed (EC). Somatosensation was modified using both a hard surface (HS) and soft surface (SS). In the EO condition, participants were asked to stare at a cross-mark that was placed at eye level and 75 cm away from their eyes. In the HS condition, participants stood barefoot on a force platform (AMTI OR6-7-1000, Watertown, Massachusetts, USA), while in the SS condition participants stood on a piece of 23mm-thick soft foam.

During the trials, participants were instructed to stand as still as possible, with their arms at their side, and their feet together. Foot placement was outlined on poster board to ensure repeatability. COP trajectories were computed from triaxial ground reaction forces and moments sampled at 100 Hz. Each trial lasted 75 seconds, with the initial 10 s and last 5 s removed to avoid initial transients and anticipation effects, respectively.

Demeaned COP time series in the anterior-posterior and the medial-lateral directions were converted to a polar coordinate system by computing the resultant distance (R) and the angle (θ) time series of the COP. Derivatives of R and θ, (i.e., $\dot{R}$ and $\dot{\theta}$) were computed using a five point differentiation (Burden & Faires, 1997).

Largest Lyapunov Exponent

To represent COP movements on the two-dimensional plane (i.e., the top surface of the force platform), four state variables would be sufficient to describe the COP dynamics as a second-order system (Pai & Patton, 1996; Kang & Dingwell, 2006). The state space vector of a COP time series is thus given as:

$$X(t_i) = [R(t_i), \dot{R}(t_i), \theta(t_i), \dot{\theta}(t_i)]^T \qquad (1)$$

where t_i is a discrete time. Each variable of $X(t_i)$ was demeaned and normalized to unit variance to account for the different units involved.

Divergence distances (d_i) of all pairs of nearest neighboring trajectories in the reconstructed state vector were computed for 1.5 s, while excluding a point on the same trajectory (details in Rosenstein et al., 1993 and Kang & Dingwell, 2006). The Euclidean distance was used as a measure of divergence distance. The parameter λ_{max}, characterizes how fast the nearest neighbor diverges on average when perturbed, and can be estimated from the slope of the mean divergence distance as:

$$y(j) = \frac{1}{\Delta t}\langle \ln d_i(j) \rangle \qquad (2)$$

in which <> denotes the mean of all $d_i(j)$, following Rosenstein et al. (1993). However, λ_{max} is not strictly definable with experimental data that are not truly chaotic, mainly because Eq (2) assumes a prominent linear relationship in the mean divergence curve (Timmer et al., 2000). After observing a typical shape among mean divergence curves, two linear functions were thus introduced to optimally fit the mean divergence curve by minimizing mean square error. Figure 1 illustrates a typical mean divergence curve of the COP, and how λ_{max} was defined from one of two linear fits. Using two linear functions did not require a fixed linear region to compute λ_{max} as in Eqn. 2, yet it is fundamentally equivalent to Eqn. 2.

Reliability

Intra-class correlation coefficients (ICC) assess relative reliability, and are determined using variance components of a two-way analysis of variance (ANOVA) model. Following Shrout & Fleiss (1979), ICC(2,1) was determined for older and younger participants in each of the four sensory conditions. ICC typically ranges from 0 to 1, and was interpreted as follows (Cicchetti & Sparrow, 1981): poor = 0.00-0.39, fair = 0.40-0.59, good = 0.60-0.74, and excellent = 0.75-1.00.

Statistical Analyses

A three-way repeated measures ANOVA was performed on λ_{max} to determine main and interactive effects of age (younger vs. older), vision (EO vs. EC), and surface condition (HS vs. SS). Significant effects were followed by post-hoc pairwise comparisons (Tukey HSD). Statistical significance was determined at $p \le .05$

RESULTS

Linear fits to compute λ_{max} yielded coefficients of determination (r^2) larger than .90 across all conditions. Age and vision had significant main effects on λ_{max} [Age: $F_{(1,30)} = 12.68$, Vision: $F_{(1,347)} = 276.66$], and the age x vision and vision x surface interactions effects were also significant [Age x Vision: $F_{(1,347)} = 11.88$, Vision x Surface: $F_{(1,347)} = 4.80$]. In general, younger participants were more stable than older participants, and altered sensory information resulted in a decrease in stability (Figure 2), excepting that somatosensation (i.e., surface condition) had no significant main effect on λ_{max}.

λ_{max} for older participants exhibited fair to good reliability (ICC: .58 ~ .73), whereas λ_{max} for younger participants showed poor to fair reliability (ICC: .34 ~ .53), as shown in Figure 3. ICCs for older participants generally showed a higher value for the EO condition than the EC condition. Comparably, ICCs for younger participants were higher for EOSS and ECHS conditions than for the EOHS and ECSS conditions.

DISCUSSION

The purpose of the study was to assess the sensitivity and reliability of a measure of local dynamic stability under varied conditions. In general, age and vision had main effects on λ_{max} (Older > Younger, EC > EO). Further, age x vision and vision x surface interaction effects were found such that modification of sensory information caused a decrease in stability. Reliability of λ_{max} was higher for the older participants than for the younger participants.

Older participants were less effective in suppressing a local perturbation (i.e., higher λ_{max}) than younger participants, independent of altered sensory conditions. That is, the older participants were less stable than the younger participants. A relative ineffectiveness of the older participants in controlling a local perturbation is potentially attributable to age-related deteriorations in sensory systems, such as a loss of precision that occurs with age (Horak & Macpherson, 1996; Laughton et al., 2003). The effects of vision on λ_{max} (EO < EC) agreed with previous evidence (Roerdink et al., 2006). Interestingly, λ_{max} was affected by surface condition (HS vs. SS) during the EC condition, but not during the EO condition. This may indicate that altered somatosensation during the EO condition was effectively compensated by other sensory inputs, considering that dynamic sensory information is typically reweighted to achieve postural control (Horak & Macpherson, 1996). Alternatively, the soft foam used may not have been sufficiently compliant to challenge postural stability during the EO condition.

Reliability of λ_{max} was found to be different between older and younger participants. A similar trend was reported with other COP-based measures (Lin et al., submitted). Interpretation of lower ICC values for younger participants requires caution, in that a low ICC can be achieved due to large within-subject variance and/or a small measurement range (Keating & Matyas, 1998). A larger within-subject variance could account for the lower ICC value among younger participants, since the same method was used to compute λ_{max} for older and younger participants. However, a recent study suggested that an acceptable level of reliability of COP-based measures be achieved with no less than five 60s trials (Doyle et al., 2007). Accordingly, low ICCs found for younger participants may be due to an insufficient number of trials.

Potential limitations of this study are: 1) the standing sway trials were relatively short (75 s), and, in particular, the duration of examined COP time series was 60 s. The results may thus not adequately reflect the true long-term behavior of λ_{max} under varied conditions; 2) the linear-fit function may be insufficient to parameterize local dynamic stability of the COP. In the case of Kang and Dingwell (2006), a double exponential fit function was used to parameterize a mean divergence curve. However, two linear functions were adaptively fit here to a mean divergence curve, and the linear-fit line to compute λ_{max} yielded $r^2 > .90$ across all conditions. Estimating λ_{max} from a linear fit thus appears reasonably valid.

In summary, the results of this study indicated main effects of age and vision, and interaction effects of age x vision and vision x surface on λ_{max}. Further, reliability of LyE varied between age groups and sensory conditions. Although reliability was considered adequate (i.e., fair to good) only for older participants, in assessing the postural control system, λ_{max} appears to have discriminant validity with respect to age and altered sensory conditions. Therefore, the nonlinear measure (λ_{max}) can supplement traditional descriptive COP-based measures so as to directly assess local dynamic stability of COP. However, further study is required to better specify any age-related differences in reliability.

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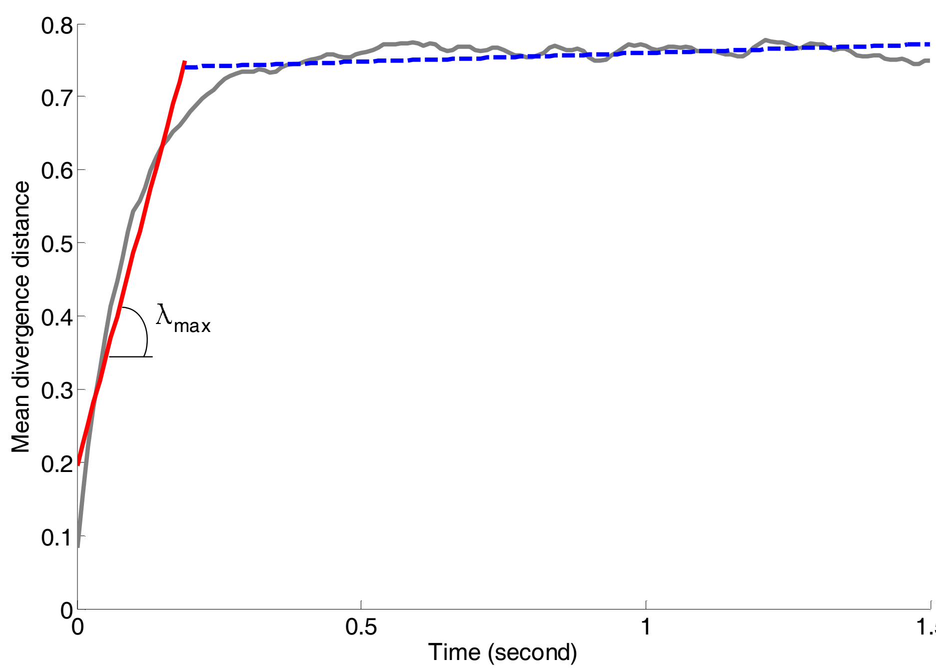

Figure 1. A typical mean divergence curve with two linear-fit lines. The slope of a solid linear-fit line represents the largest Lyapunov exponent (λ_{max}).

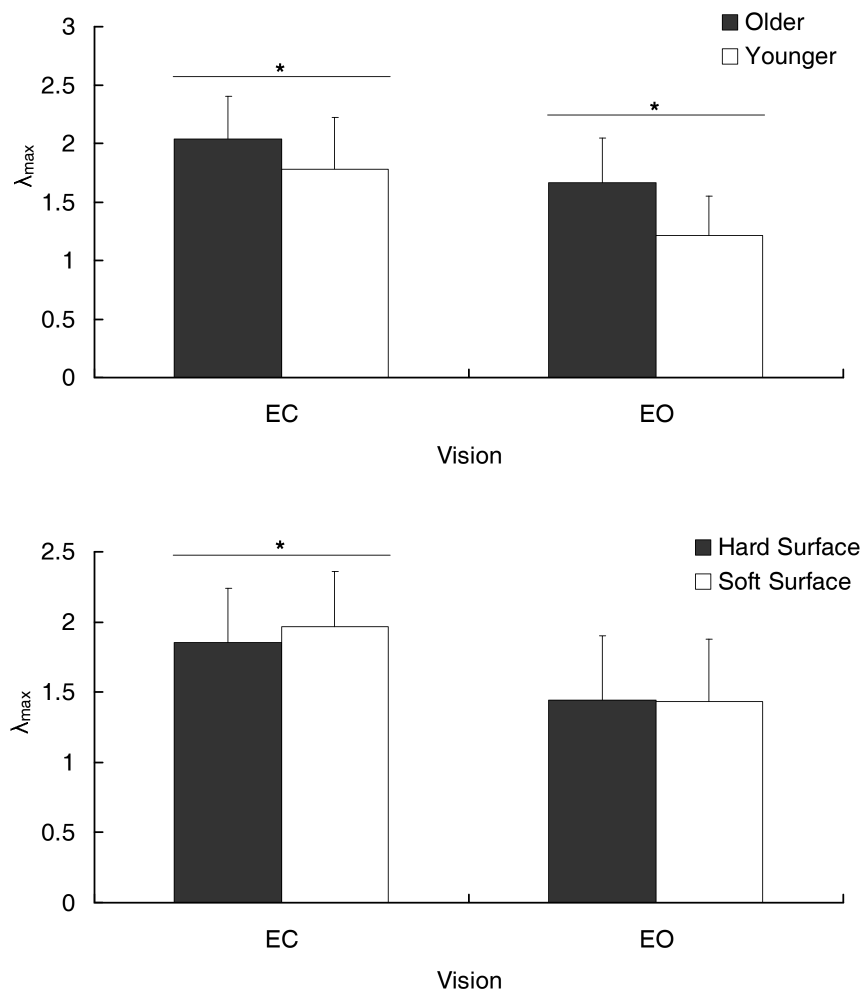

Figure 2. Effects of age, vision and surface on the largest Lyapunov exponent (λ_{max}). The effects of age, vision, age x vision and vision x surface were significant. Significant differences between age or surface conditions are indicated by *, and error bars indicate standard deviations.

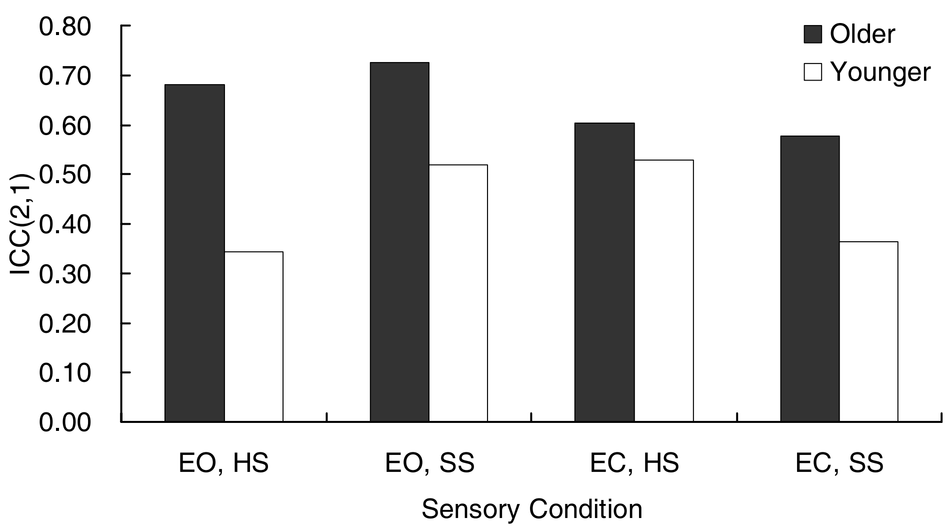

Figure 3. ICCs for older and younger participants (EO: eyes-open, EC: eyes-closed, HS: hard surface, SS: soft surface).