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CHANGES IN CENTER-OF-PRESSURE DYNAMICS DURING UPRIGHT STANDING RELATED TO DECREASED BALANCE CONTROL IN YOUNG ADULTS: FRACTIONAL BROWNIAN MOTION ANALYSIS

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We investigated the relationships between the ability to maintain balance in an upright stance and center-of-pressure (COP) dynamic properties in young adults. Included in this study were 10 healthy male subjects in each of two groups with respect to balance ability. Balance ability was evaluated according to the length of time a subject stood on one leg with his eyes closed. The means and ranges of this one-leg balancing time were 17.9 s (3-43 s) and 118.3 s (103-120 s) for the off-balance and balance groups, respectively. The time-varying displacements of the COP under a subject's feet during quiet two-leg (normal) standing were measured by an instrumented force platform. Each subject was tested in both the eyes-open and eyes-closed conditions. The COP trajectories were analyzed as fractional Brownian motions according to the procedure of 'stabilogram-diffusion analysis', proposed by Collins and De Luca (1993). The extracted parameters were the effective diffusion coefficients (D) for the short-term (less than about 1.0 s) and long-term intervals, respectively, as well as the Hurst exponents (H) for the short-term and long-term intervals, and some critical-point coordinates (i.e., critical mean square displacements and critical time intervals).

The off-balance group showed significantly higher values for short-term D, short-term H, and critical mean square displacements than the balance group. No significant differences between the groups were found in the long-term D and H or in the critical time intervals. That is, for the off-balance subjects, an increase in the stochastic activity and positively correlated (persistent) behavior of the postural sway during shorter timescales may cause postural instability. These results suggest that the difference in balance ability for young adults is related to the open-loop (i.e., short-term) control mechanisms but not to the corrective feedback (i.e., long-term) mechanisms used to maintain balance in an upright stance.

Keywords: standing posture; off-balance; center-of-pressure; random-walk model

INTRODUCTION

The ability to maintain balance in a bipedal stance is fundamental to several essential activities in daily living. Deficiencies in postural control can lead to instability, falls, and injury. Falls are one of the major problems in medical care, particularly for aged populations. Past studies have focused on postural sway during quiet standing as a measure of stability or balance. Significant increases in postural sway have been observed in the elderly (e.g., Hasselkus and Shambes, 1975; Sheldon, 1963). Fernie et al. (1982) suggested that postural sway can be an indicator of a tendency to fall in the

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elderly. In the case of young adults, the predictive importance of testing postural sway during normal standing to find persons at risk of falls in the future is under controversy. Nevertheless, even some healthy young adults have distinctly increased postural sway and/or decreased balance control. It is important to clarify the relationships between characteristics of postural sway and the ability to maintain balance in an upright posture for young adults, in order to prevent decreases in balance control with aging. More observations, using populations of diverse ages, are also needed. These findings may provide valuable information with respect to training regimens to improve balance ability as an element of health-related physical fitness.

Postural sway is typically estimated using a force platform to record the center-of-pressure (COP) under a subject's feet. The COP is equal and opposite to a weighted average of the location of all downward forces due to postural muscular action acting on the force platform (Winter, 1990). Several methods have been proposed for the calculation of posturographic parameters from COP trajectories. Many former studies were limited to the analysis of these plots using summary statistics. A large number of summary statistics, such as maximum distances, root mean squared distances, and/or total excursions traversed by the COP, have been employed to characterize spontaneous postural sways. These parameters tend to have reasonable reliability but limited sensitivity to some factors (e.g., age and vision) that may affect postural control (Prieto et al., 1996).

More recently, Collins and De Luca (1993) introduced a new method for analyzing COP trajectories, known as stabilogram-diffusion analysis (SDA). This method provides a further understanding of COP dynamic properties, and the parameters it establishes can be interpreted in a physiologically meaningful way. A number of studies have determined normative values for the various SDA parameters, and have identified systematic changes in SDA parameters as a function of visual input for postural control (Collins and De Luca, 1995a; Riley et al., 1997a), age (Collins et al., 1995a), space flight (Collins et al., 1995b), touch and vision (Riley et al., 1997b), visual feedback effects (Rougier, 1999), blind subjects (Rougier and Farenc, 2000), adolescent growth (Wolff et al., 1998), and disease state (Mitchell et al., 1995). But one unresolved question is exactly how decreased balance control influences COP dynamic properties derived from the SDA. The purpose of the present study was to investigate the relationships between the ability to maintain standing balance and the dynamic properties of COP in young adults.

METHODS

Subjects

Prior to the laboratory experiment, an initial one-leg balance test with eyes closed was given to 628 male college students as a screen to assess their ability to control their balance. One-leg standing balance was measured as the length of time that a subject was able to maintain his balance while standing on one foot, with the other leg slightly lifted forward, the foot off the ground, and each hand placed on the hips. The test was stopped at 120 s even if the subject could have maintained the test position longer. From the results, the subjects were classified into three groups, depending on their balancing times: off-balance (1-45 s), intermediate (46-89 s), and balance (90-120 s). Finally, we selected 20 healthy male subjects for the off-balance group (n=10) and the balance group (n=10) for the laboratory experiment. A physical fitness profile for each group is shown in Table 1. No significant differences between the groups were found in the physical fitness profiles. The 20 subjects selected had similar ages (total mean age: 18.6±0.69 years) and body dimensions (total mean body weight: 62.2±8.16 kg; total mean body height: 172.3±5.47 cm). All subjects were free of any significant gait or postural disorders. Informed consent was obtained from each subject before participation in the experiment.

As a check, the one-leg balance test was re-run under laboratory conditions. The means and ranges of the one-leg balancing times were now 17.9 s (ranging from 3-43 s) and 118.3 s (ranging from 103-120 s) for the off-balance and balance groups, respectively. There was a statistically sig-

Table 1. Physical fitness profiles of off-balance (*n*=10) and balance (*n*=10) subjects

	Off-balance group		Balance group	
	Mean	S.D.	Mean	S.D.
50 meter run (s)	7.5	0.50	7.1	0.43
Standing broad jump (cm)	225.8	23.61	226.5	12.03
Handball throw (m)	26.1	4.79	25.1	4.63
Sit-up (1/s)	25.2	3.19	29.2	5.16
Side-step (1/s)	54.1	7.52	58.8	5.87
Grip strength (kg)	42.0	6.51	43.8	8.23
Back strength (kg)	135.8	28.46	145.7	29.23
Trunk flexion (cm)	50.6	11.15	47.0	8.93

Sit-up and side-step performances were evaluated by the number of repetitions achieved in 20 s. In the trunk flexion test, the subjects sat on the floor with legs extended and the back against a wall, and then reached forward as far as possible.

nificant difference between the two groups in the one-leg balancing time ($p<0.01$). Thus, it can be assumed that the two groups differed in their ability to control balance.

Experimental conditions

The time-varying displacements of the COP under each subject's feet during quiet 'two-leg' (normal) standing were measured with an instrumented force platform (KYOWA ECG-S-1KNSA1). Subjects participated in a set of postural tasks. The first task, the visual or 'eyes-open' task, consisted of standing barefoot in a standardized stance on the platform, with the arms hanging relaxed at the sides. In the standardized stance, each of the subject's feet was abducted 5 degrees and the heels were separated mediolaterally by a distance of 3 cm. This stance was chosen to minimize the influence of foot position on the amount of postural sway and the mean position of COP (Kirby et al., 1987). Subjects were instructed to focus on a small red square (2.0 x 2.0 cm) placed on a screen at eye level for each subject, at about 2 m from the platform. The second task, a no-vision or 'eyes-closed' task, was the same as the first one except that the subjects performed the task with the eyes closed and fully covered by an eye mask. The mediolateral (ML) and anteroposterior (AP) COP coordinates on the platform were collected for a trial duration of 30 s and sampled at 100 Hz, yielding total data points of 3,000. The subjects were asked to stand still on the platform for about 5 s before data collection began for each trial. Ten trials of each of the two vision conditions were conducted. The order of the presentation of the vision conditions was counterbalanced across the subjects. Rest periods of 1 min were provided between each trial.

The noise characteristics of the KYOWA force platform were measured by placing a test mass of 60 kg on the force platform. The kinetic data were sampled at 100 Hz for 30 s. In the absence of any movement, the platform produced a noise signal that was less than ±0.3 mm in magnitude in the measured coordinates of the COP of the test mass. This value was considerably less than the subjects' postural fluctuations during quiet standing on the force platform.

Stabilogram-diffusion analysis (SDA)

Prior to the data analysis, the measured COP coordinates for each trial were translated so that the origin corresponded to the mean coordinates of COP trajectories along the ML and AP directions. This translation allows us to assume that the means of COP displacements are equal to approximately 0 in the ML and AP directions, respectively, and hence the dynamic behavior of the COP trajectories in each direction can be considered as a one-dimensional random walk. Then, the COP trajectories in the ML and AP directions were analyzed separately according to the SDA procedure. A more complete description of SDA can be found in Collins and De Luca (1993; 1995b).

In the first step of SDA, the displacement analysis was carried out on the COP time series for each trial, in which the square of the displacements between all pairs of data points separated in time by a specified time interval Δt were computed (see Figure 1a). The square displacements were then averaged over the number of intervals of size Δt making up the COP time series in the trial. This process was repeated for specified different values of Δt. The mean square displacement is defined as a function of the time interval Δt for a COP trajectory. It is calculated for a specified Δt spanning m data intervals as follows,

$$\left\langle \Delta x^2 \right\rangle_{\Delta t} = \frac{\sum_{i=1}^{N-m} \left(\Delta x_i\right)^2}{N-m}, \qquad \Delta x_i = x_{i+m} - x_i \qquad (1 \le m < N) \qquad [1]$$

where x is the ML or AP displacements and N is the total number of data points in the trial. In this study, the mean square displacements for each trial were computed for the time intervals ranging from 10 ms (m=1) to 10 s (m=1,000), in steps of 10 ms, depending on the sampling rate. This range of time intervals was chosen because it was sufficient to capture the long-term behavior of the postural control system, and the inclusion of longer time intervals in the analysis may have introduced unreliable results (Collins and De Luca, 1995a). Mean square displacement values were then averaged for the 10 trials, resulting in one resultant or mean stabilogram-diffusion series per subject per visual task (i.e., either the eyes-open or the eyes-closed tasks). Figure 1b illustrates a plot of mean square COP displacement $<\Delta x^2>$ versus time interval Δt, known as a ‘stabilogram-diffusion plot’. The symbols < > denote an average over time or an ensemble average over a large number of samples. For a particular subject per visual task, one stabilogram-diffusion plot was obtained from the resultant or mean stabilogram-diffusion series computed above.

In the second step of SDA, an estimation of various posturographic parameters was calculated using the resultant stabilogram-diffusion plots. In order to parameterize the resultant stabilogram-diffusion plots, two regions (a short-term region and a long-term region) were identified in terms of time interval Δt. These regions are separated by a transition or critical period over which the slope of the stabilogram-diffusion plot changes considerably. Posturographic parameters, estimated from the resultant stabilogram-diffusion series, were the diffusion coefficients (D), Hurst exponents (H), and some critical point coordinates (i.e., critical mean square displacements ($<\Delta x^2>_c$) and critical time intervals (Δt_c)).

Diffusion coefficients D reflect the average level of stochastic activity or variability of the COP trajectories. According to the general expression of the Einstein relation for Brownian motion, the diffusion coefficient D is given as follows,

$$\left\langle \Delta x^2 \right\rangle = 2D\Delta t \qquad [2]$$

which shows that the mean square displacement $<\Delta x^2>$ of a one-dimensional random walk is proportional to the time interval Δt. The diffusion coefficient D is an accurate index of stochastic activity only when the Hurst exponent H equals 0.5, as mentioned below, which is rarely the case with quiet-standing COP trajectories. Thus, D is referred to as the effective diffusion coefficient. Collins and De Luca (1995a) demonstrated that from a physiological standpoint, the short-term D and long-term D characterize the effective stochastic activity of open-loop and closed-loop postural control mechanisms, respectively. Effective diffusion coefficients D are calculated from the slopes of the resultant linear-linear plots of $<\Delta x^2>$ versus Δt.

Hurst exponents H quantify the correlation between past and future increments of the COP displacements over different time scales. The Hurst exponent H is given by generalization of Equation 2 involving the scaling law as follows,

$$\left\langle \Delta x^2 \right\rangle \propto \Delta t^{2H} \qquad [3]$$

H can be any real number ranging from 0 to 1. If H=0.5, then the displacement increments are statistically independent; this is the random walk or classical Brownian motion. If H>0.5, past and future increments are positively correlated, and then diffusion is enhanced (persistence) (Kantz and Schreiber, 1997). In this case, an increasing (or decreasing) trend in the past implies an increasing (or decreasing) trend in the future. On the other hand, if H<0.5, the stochastic process is negatively correlated and then diffusion is suppressed (antipersistence) (Kantz and Schreiber, 1997). In this case, increasing (or decreasing) trends in the past imply decreasing (or increasing) trends in the future, on average. Collins and De Luca (1993) suggested that from a physiological standpoint, the short-term H (which is typically greater than 0.5) characterizes the drift-like dynamics of open-loop postural con-

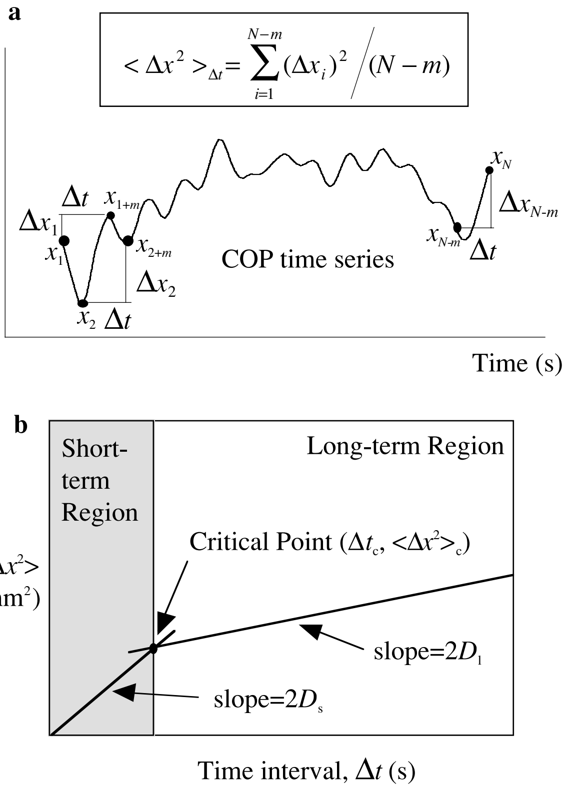

Fig. 1. a) Schematic diagram showing the method for calculating the mean square displacement $<\Delta x^2>$ as a function of the time interval Δt for a COP time series in the mediolateral (ML) and anteroposterior (AP) directions, characterized by N data points. For 30 s trials sampled at 100 Hz, yielding N=3,000 data points, the mean square displacement was calculated for a specified Δt ranging from 10 ms (m=1) to 10 s (m=1,000) in 10-ms steps, depending on the sampling rate. b) A typical resultant stabilogram-diffusion plot generated from COP time series (Collins and De Luca, 1993). The linear plot is utilized to estimate the effective diffusion coefficients (short-term D_s, long-term D_l) and the critical point coordinates (Δt_c, $<\Delta x^2>_c$).

trol mechanisms. In contrast, the long-term H (which is typically less than 0.5) characterizes the antidrift-like dynamics of closed-loop postural control mechanisms. Hurst exponents H are calculated from the slopes of the resultant log-log plots of $<\Delta x^2>$ versus Δt. It should be noted that effective diffusion coefficients D as well as the Hurst exponents H are computed separately for each of the short-term and long-term regions of the resultant stabilogram-diffusion plots.

Finally, critical point coordinates (i.e., critical mean square displacements $<\Delta x^2>_c$ and critical time intervals Δt_c) approximate the transition point where the short-term and long-term regions can be separated from each other. That is, these coordinates approximate the temporal and spatial characteristics of the region over which the postural control system switches from open-loop control to closed-loop control (Collins and De Luca, 1993).

In the present study, the effective diffusion coefficients D and Hurst exponents H were computed as follows. The stabilogram-diffusion series were first fitted with the linear model:

$$\left\langle \Delta x^2 \right\rangle = \beta_0 + \beta_1 \Delta t \qquad [4]$$

where $\beta_1=2D$, and then fitted with the exponential model:

$$\left\langle \Delta x^2 \right\rangle = e^a \Delta t^{2H}. \qquad [5]$$

The respective slopes of β_1 in Equation 4 and $2H$ in Equation 5 were determined by utilizing the least squares method over the defined short-term and long-term portions. The critical point coordinates were estimated as the intersection point of the two straight lines fitted to the respective short-term and long-term regions of the linear plots using the resultant or mean stabilogram-diffusion series. In fact, the two line fittings to the short-term and long-term regions on each of the linear-linear and log-log plots, as well as the determination of the critical point coordinates, were computed with a specifically written computer routine using LabVIEW 5.1 (NATIONAL INSTRUMENTS). This program provided point-by-point selection of data to find the optimum location of the critical point and simultaneously display the mean residual as an index of the goodness-of-fit of the regression lines. Using this program, a single investigator visually determined the location of the critical point coordinates, in which the mean residuals for both line fits to the short-term and long-term regions were minimized using least squares criteria. All SDA parameters were then computed. The coefficient of determination values, r^2, of the regression lines fitted to the short-term D, long-term D, short-term H, and long-term H, ranged from 0.97-0.99, 0.52-0.99, 0.98-0.99, and 0.60-0.99, respectively. A significant majority of r^2 values (except for a few cases for the long-term D and H) were greater than 0.95.

RESULTS

Mean stabilogram-diffusion plots

The resultant stabilogram-diffusion series, obtained from the 10 different trials for 30 s, were averaged for the off-balance and the balance subjects for each of the two visual tasks in order to generate the mean stabilogram-diffusion plots (Figure 2). The mean plots would allow for a qualitative assessment of typical pattern of changes in the COP dynamic profiles as related to the balance ability and the visual condition. The mean stabilogram-diffusion curves changed slope after a transition or critical region at the shorter time interval (approximately 1 s). This general feature was present in each resultant stabilogram-diffusion plot of each of the 20 subjects. Differences between the off-balance and the balance groups in the mean curves over the respective short-term and long-term regions were visually identified, as were differences between the visual conditions. In both the ML and AP directions, the slopes over the short-term region (Δt<~1.0 s) were steeper for the off-balance group than for the balance group under either visual condition. It should be noted that the short-term slopes of the eyes-open condition for the off-balance group were very close to those of the eyes-closed condition for the balance group. The long-term slopes (Δt>~1.0 s) for the off-balance group seemed to be greater than those for the balance group in the AP direction. In contrast, the long-term

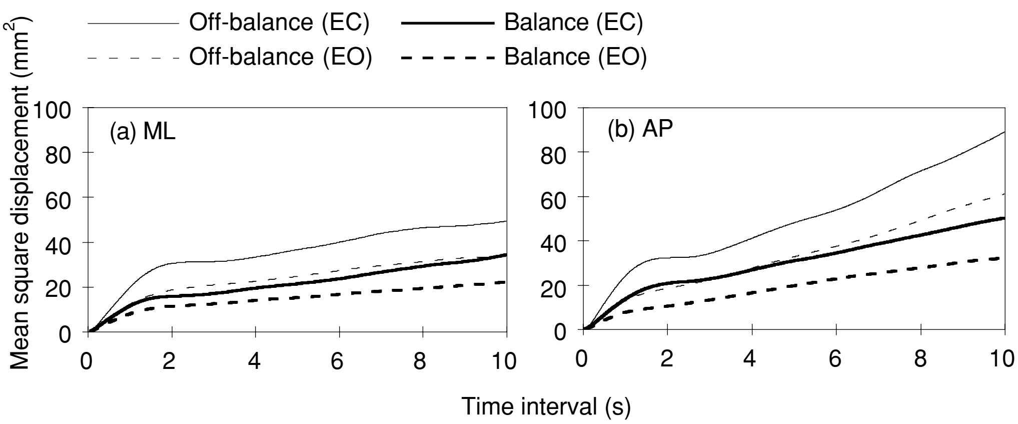

Fig. 2. Mean stabilogram-diffusion plots for the off-balance and balance groups for the eyes-open (EO) and eyes-closed (EC) conditions. The mean plots were generated from ten different 30 s COP time series and then averaged for each group for each visual condition.

slopes in the ML direction for the off-balance group were similar to those for the balance group.

SDA parameters

The differences associated with visual condition and balance ability that were visually identified with the mean stabilogram-diffusion plots (Figure 2), were statistically tested. Two-way mixed design (one between, one within) ANOVAs were performed on the SDA parameters. The between factor was balance ability (off-balance group vs. balance group), and the within factor was visual condition (eyes open vs. eyes closed). The means and standard deviations of the SDA parameters for both groups and both visual conditions are shown in Table 2 (for the ML direction) and Table 3 (for the AP direction). It should be noted that for both balance groups and both visual conditions, the short-term H values were greater than 0.5, and that the COP diffusions exhibited persistence over the short-term region. In contrast, the long-term H values were smaller than 0.5, indicating antipersistence behaviors of the COP diffusions.

As shown in Table 2, in the ML direction, statistically significant main effects of balance ability were found for the short-term D ($F(1, 18) = 5.86$, $p< 0.05$), short-term H ($F(1, 18) = 4.46$, $p< 0.05$), and critical mean square displacement ($F(1, 18) = 4.92$, $p< 0.05$). The mean values of these three parameters were larger for the off-balance group than for the balance group. The long-term D, long-term H, and critical time interval showed no statistically significant differences between the off-balance and balance groups. With respect to the main effects of the visual conditions, the short-term D ($F(1, 18) = 27.06$, $p< 0.01$), long-term D ($F(1, 18) = 5.87$, $p< 0.05$), short-term H ($F(1, 18) = 9.25$, $p< 0.01$), and critical mean square displacement ($F(1, 18) = 19.03$, $p< 0.01$) were significantly greater for the eyes-closed condition than for the eyes-open condition.

In the AP direction, statistically significant main effects of balance ability were found for the same parameters as seen in the ML direction. That is, the short-term D ($F(1, 18) = 13.00$, $p< 0.01$), short-term H ($F(1, 18) = 4.49$, $p< 0.05$), and critical mean square displacement ($F(1, 18) = 8.63$, $p< 0.01$) were significantly greater for the off-balance group than for the balance group. No significant group difference was found for the long-term D, long-term H, or critical time interval. With respect to the main effects of the visual conditions, the short-term D ($F(1, 18) = 58.19$, $p< 0.01$), short-term H ($F(1, 18) = 38.50$, $p< 0.01$), and critical mean square displacement ($F(1, 18) = 22.60$, $p< 0.01$) were significantly greater for the eyes-closed condition than for the eyes-open condition. In contrast, the long-term H ($F(1, 18) = 18.75$, $p< 0.01$) was smaller for the eyes-closed than for the eyes-open condition.

Table 2. Means and standard deviations for the parameters in the ML direction obtained from the stabilogram-diffusion analysis for visual conditions and balance ability groups.

	Visual condition			Balance ability			Interaction
	Eyes-open	Eyes-closed	*p*	Off-balance	Balance	*p*	*p*
Ds	5.42 ± 2.60	8.59 ± 5.16	0.001	8.85 ± 5.21	5.16 ± 2.09	0.026	0.080
Dl	0.83 ± 0.55	1.24 ± 1.04	0.026	1.15 ± 0.58	0.92 ± 1.05	0.502	0.702
Hs	0.76 ± 0.05	0.78 ± 0.05	0.007	0.79 ± 0.05	0.75 ± 0.04	0.049	0.810
Hl	0.21 ± 0.07	0.22 ± 0.08	0.500	0.23 ± 0.06	0.21 ± 0.09	0.497	0.793
CT	1.20 ± 0.43	1.09 ± 0.32	0.131	1.20 ± 0.46	1.09 ± 0.28	0.481	0.432
CD	12.88 ± 9.34	18.56 ± 15.11	0.001	21.19 ± 16.10	10.25 ± 3.26	0.040	0.016

D, effective diffusion coefficient (mm^2/s); H, Hurst exponent; The subscript s and l show parameters in the short-term and long-term regions, respectively. CT, critical time interval (s); CD, critical mean square displacement (mm^2); *P*, probability of significance for *F* tests.

Table 3. Means and standard deviations for the parameters in the AP direction obtained from the stabilogram-diffusion analysis for visual conditions and balance ability groups.

	Visual condition			Balance ability			Interaction
	Eyes-open	Eyes-closed	*p*	Off-balance	Balance	*p*	*p*
Ds	5.84 ± 2.63	10.63 ± 4.96	0.001	10.53 ± 5.09	5.93 ± 2.56	0.002	0.026
Dl	2.01 ± 1.36	2.71 ± 2.93	0.178	3.05 ± 2.86	1.66 ± 1.23	0.124	0.697
Hs	0.78 ± 0.04	0.81 ± 0.04	0.001	0.81 ± 0.03	0.78 ± 0.04	0.048	0.642
Hl	0.35 ± 0.10	0.29 ± 0.10	0.001	0.33 ± 0.10	0.31 ± 0.10	0.748	0.809
CT	0.82 ± 0.32	0.93 ± 0.26	0.224	0.89 ± 0.29	0.87 ± 0.30	0.855	0.634
CD	8.04 ± 6.10	15.81 ± 9.45	0.001	14.05 ± 10.68	9.80 ± 5.90	0.009	0.238

D, effective diffusion coefficient (mm^2/s); H, Hurst exponent; The subscript s and l show parameters in the short-term and long-term regions, respectively. CT, critical time interval (s); CD, critical mean square displacement (mm^2); *P*, probability of significance for *F* tests.

The two-way interaction between balance ability and visual condition was significant in the critical mean square displacement in the ML direction ($F(1, 18) = 7.08$, $p< 0.05$) and in the short-term D in the AP direction ($F(1, 18) = 5.92$, $p< 0.05$). Figure 3 displays the enhancement of the effects of the visual conditions for each group: that is, the eyes-closed condition had a greater influence on the off-balance group than on the balance group.

DISCUSSION

In the present cross-sectional study, using the posturographic parameters based on SDA, we demonstrated the presence of changes in the COP dynamic behaviors related to decreased balance control in healthy young adults. Collins and De Luca (1993), who first introduced the SDA of COP trajectories, hypothesized that postural control involves open-loop control mechanisms over a short-term region (arising from delays in feedback processing that allows the integration of sensory information when there is no danger of falling) and closed-loop control mechanisms over a long-term region (providing for corrective adjustments). The two observable regions of the stabilogram-diffu-

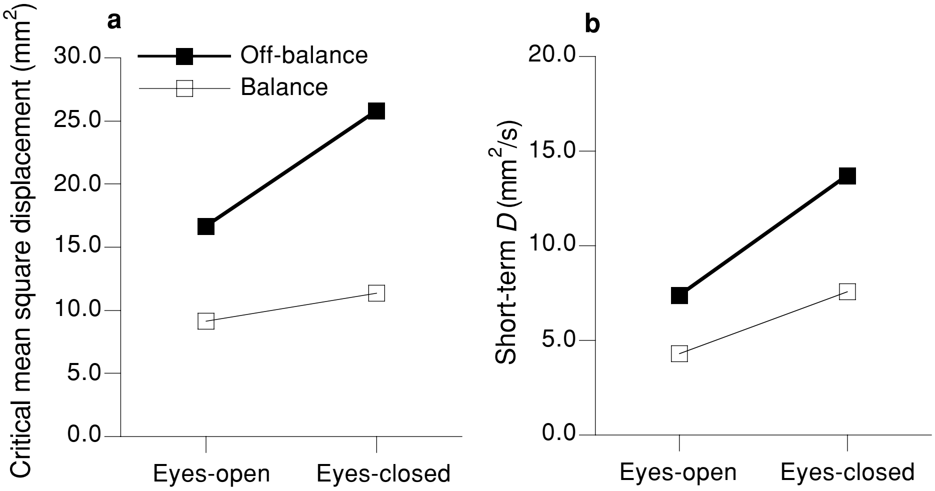

Fig. 3. The two-way interaction between visual condition and balance ability: a) means of the critical mean square displacement in the ML direction and b) means of the short-term *D* in the AP direction. The mean values were calculated for each group for each visual condition.

sion plot can be interpreted as corresponding to the respective control regimes. The present results can be interpreted according to the open-loop (short-term) and closed-loop (long-term) postural control hypothesis.

As mentioned above, the off-balance group showed significantly larger values for short-term *D* than the balance group (see Tables 2 and 3). This suggests that for the off-balance subjects, the effective stochastic activity of open-loop postural control mechanisms increased in both the AP and ML directions, when compared to the balance subjects. The less stable upright posture of the off-balance subjects may be due to the increased stochastic activity over shorter timescales. For the off-balance subjects, the unstable state caused by the increased stochastic activity can be magnified by the no-vision condition, particularly in the AP direction (see Figure 3). Additionally, the off-balance group showed significantly higher values for short-term *H* than the balance group. This suggests that for the off-balance subjects, the positively correlated behavior (i.e., increased levels of persistence) of open-loop control mechanisms increased in comparison with the balance subjects.

The off-balance subjects were also characterized by significantly larger critical mean square displacements and equivalent critical time intervals. These differences were directly associated with the steeper slopes of the stabilogram-diffusion plots over the short-term region. From the perspective of probability, when the COP behavior is positively correlated (persistence), i.e., $H>0.5$, the COP moving in a particular direction for some t_0 will tend to continue in the same direction for $t>t_0$. In the case of the positively correlated COP behavior over the short-term region, an increase in the mean square displacements over equivalent time intervals suggests that the COP trajectories will continue to move in the same direction but with larger velocity, on average. It seems reasonable to conclude that over short-term intervals during quiet standing, young adults with decreased balance ability have a greater tendency to move or drift away from a relative equilibrium point with a larger velocity, following a perturbation.

Finally, considering the long-term *D* and *H*, it was found that the off-balance subjects were similar to the balance subjects. This result suggests that the steady-state behavior of closed-loop (long-term) postural control mechanisms cannot readily change in spite of the difference in balance ability. The present findings, therefore, support the idea that the increased stochastic activity seen over shorter timescales may be responsible for postural instability. This view reinforces the importance of investigating characteristics of the COP dynamics during an undisturbed stance in the context of sequential changes with advancing age. One way to do this would be to examine postural control dynamics for diverse age groups and large populations.

Physiological interpretations

Previous posturographic studies indicated that postural sways reflect a perception-action strategy involving exploratory and performatory behavior. Since the sways provide an individual's perceptual systems with a constant source of stimulation, postural sways may serve an exploratory role (Riccio and Stoffregen, 1988; Riley et al., 1997a). Performatory behaviors are those actions intended to achieve a goal, such as maintaining an upright posture. Riley and his colleagues (1997b) hypothesized that the COP behaviors over the short timescales (i.e., persistence) and long timescales (i.e., antipersistence) are exploratory and performatory, respectively. Exploratory behaviors are those that obtain information about the body (proprioception) and about the body's orientation to the surroundings (exprioception), while performatory behaviors are those that obtain information in order to maintain postural stability. From the physiological viewpoint, we consider exploratory behavior as an 'idling-like phenomenon', in which the neuromuscular activation is set to a specified level to react as quickly as possible to suddenly increased postural perturbation. In this view, the magnitude of persistence behaviors over short timescales may reflect sensitivity to sensory information from the vestibular, somatosensory, and visual systems, when the activation level of the musculoskeletal system is equivalent. A higher level of the persistence of COP behaviors over short timescales represents a lower level of sensitivity to sensory information from the visual, vestibular, and somatosensory systems. According to this hypothesis, one possible interpretation of the present findings is that young adults with decreased balance ability have lower sensitivity in such sensory systems or lower reliance on sensory information obtained from exploratory behavior during periods of undisturbed stance. To clarify these problems, more physiologically oriented examinations are needed, particularly measurements of response times to stimuli.

CONCLUSIONS

The SDA approach revealed the existence of significant changes in COP dynamic properties during upright standing related to decreased balance control in young adults. The present study demonstrated that the stochastic activity and/or positively correlated behavior (i.e., increased levels of persistence) of the open-loop (short-term) postural control mechanisms increase with decreased balance control. Also found was that the steady-state behavior of the closed-loop (long-term) postural control mechanisms cannot readily change with decreased balance control. Finally, these findings were obtained from an experiment with a cross-sectional design. There is a continuing need for other, longitudinal, studies that investigate characteristics of the COP dynamic behavior in the context of sequential changes with advancing age.

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