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A retrospective analysis of balance control parameters in elderly fallers and non-fallers

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ABSTRACT

Background: A cross-sectional retrospective study of parameters reflecting balance function in elderly fallers and non-fallers was conducted to better understand postural control mechanisms in individuals prone to falls.

Methods: Ninety-nine old adults (65–91 years, mean age 78.4 (SD 5.7)) from two self-care residential facilities participated in the study. Foot center-of-pressure (CoP) displacement data were collected during narrow base upright stance eyes closed conditions and analyzed using summary statistics and Stabilogram-Diffusion Analysis (SDA) for mediolateral (ML) and anteroposterior (AP) directions. Subjects were instructed to minimize body sway.

Findings: Twenty-nine of the subjects reported at least one fall and 69 subjects reported no falls in the past six months. The SDA showed significantly higher short-term diffusion coefficients and critical displacements in fallers in the ML but not the AP direction. Mean sway area and ML-CoP sway range were also larger in fallers.

Interpretation: The greater ML critical displacement seen in fallers suggests that balance corrections on average occurred at higher sway amplitudes in this population. This is consistent with an ML decrease in the sensitivity of their postural control system. A higher short-term diffusion coefficient is consistent with increased muscle stiffness, a possible compensation for lost control sensitivity. Testing balance function under narrow stance conditions provides a modest increase in task difficulty that may help reveal pre-conditions of the balance control system that could increase the risk of falls.

1. Introduction

Fall-related injuries constitute a serious public health problem associated with human suffering as well as high costs for society (CDC, 2000). Age-related deterioration of balance control mechanisms due to aging leads to balance impairment that can contribute to falls and limitations of mobility, and eventually cause severe disability (Mahoney, 1998). Increased postural sway in older adults has been demonstrated even during quiet standing (Baloh et al., 1994; Collins et al., 1995). Using center of pressure (CoP) summary statistics, Melzer et al. (2004) found that parameters of mediolateral (ML) sway in narrow base stance could identify elderly persons who reported two or more falls in the past six months. Fernie et al. (1982) found a significantly greater average speed of sway in older adults who had fallen one or more times in a year compared with those who had not fallen. In a prospective study, Maki et al. (1994) found that the ML sway amplitude under no vision (blindfolded) condition was a moderately accurate predictor of future falls, even in individuals with no recent history of falling. In a review, Piirtola and Era (2006) found nine original prospective follow-up studies using the force platform as a tool to measure postural balance. In five studies fall-related outcomes were associated with some force platform measures. For the various parameters derived on the basis of the force platform data, the mean speed of the ML movement of the CoP during normal standing with eyes open and closed, the mean amplitude of the ML movement of the CoP with eyes open and closed, and the root-mean-square value of the ML displacement of CoP were the indicators that showed significant associations with future falls. None of the research studies introduced above (Maki et al., 1994; Melzer et al., 2004; Piirtola and Era, 2006) provide an indication of the underlying postural control mechanisms. Unfortunately, the use of traditional CoP-based summary statistics in these studies does not allow a specific understanding of underlying postural control mechanisms related to falls. In comparison, in the present study Stabilogram-Diffusion Analysis (SDA) was used (Collins and De Luca, 1993; Collins et al., 1995). SDA is based on underlying trends and persistence in the data that are not observed when only traditional CoP sway measures

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are studied. These findings have been used to discuss probable control strategies of postural sway, and include both open-loop and closed-loop control (Collins and De Luca, 1993; Collins et al., 1995). The transition between open-loop and closed-loop control has been termed the critical point, the coordinates of which reflect the average time interval (critical time, Ct_x) and sway displacement (critical displacement, Cd_x) at which closed-loop control begins to dominate sway behavior. The SDA method has been adopted by a number of research groups who have shown that SDA parameters are sensitive to the effects of age (Collins et al., 1995; Wolff et al., 1998), vision (Collins and De Luca, 1995; Rougier and Farenc, 2000), and Parkinsonism (Mitchell et al., 1995).

Laughton et al. (2003) were unable to find significant differences in SDA parameters of postural control mechanisms in normal stance between old adults who reported falling and non-fallers. Based on previous research studies introduced above (Maki et al., 1994; Melzer et al., 2004; Piirtola and Era, 2006), we argue that testing in “normal” wide base stance is insensitive to balance function allowing the elderly fallers to compensate using biomechanical or visual compensations. Thus, differences in postural control in Laughton et al. (2003) may pass undetected. Interpretation of the SDA may offer more insight into the nature of the process controlling the CoP trajectories and may be more sensitive than the traditional CoP measures: detecting significant differences between fallers and non-fallers. We believe that narrow base eyes blindfolded condition, known to interfere with stability, will better reveal underlying deficiencies in balance control in old adults that reported falling. Thus we hypothesized that: older persons who have had recent unexplained falls (1) will show greater sway displacement before closed-loop feedback mechanisms are called into play and (2) Stabilogram-Diffusion Analysis (SDA) parameters would be different for medio-lateral (ML) but not anteroposterior (AP) directions.

2. Methods

Twenty-nine subjects who reported at least one unexpected fall over the past six months and 69 non-fallers (aged 65–91 years) from protected retirement homes in Beer-Sheva, Israel, were assessed. A fall was defined as “an event, which results in a person coming to rest inadvertently on the ground or other lower level regardless of whether an injury was sustained, and not as a result of a major intrinsic event or overwhelming hazard” (Tinetti et al. 1988). The physical, mental, and performance characteristics and differences between fallers and non-fallers are described in Table 1. No significant differences were present between fallers and non-fallers in their age, Mini-Mental State Examination score, number of medications taken, Berg Balance score, Timed Get up and Go Test, and weight (Table 1).

Prior to their inclusion in the study participants provided informed consent, in accordance with approved procedures by the Helsinki-IRB ethics committee in Soroka Medical Center, Beer-Sheva, Israel. Prescreening and testing procedures were performed at the recruitment facilities. Inclusion criteria were: (a) able to stand independently for 90 s and (b) able to walk 10 m (with cane if necessary). Exclusion criteria were: (a) serious visual impairment, (b) inability to ambulate independently or with a cane, (c) score less than 24 on the Mini-Mental State Examination, indicating moderate to severe dementia, and (d) impaired communication capabilities.

Table 1
Subject characteristics.

Characteristic, mean (SEM)	Fallers $N=29$	Non-fallers $N=69$	P
Age (years)	76.9 (1.3)	78.9 (0.65)	0.12
Gender (female/male)	9/20	18/51	NS*
Mini-mental test score	29.2 (0.17)	28.9 (0.12)	0.26
Number of medications	5.3 (0.59)	4.8 (0.36)	0.47
Weight (kg)	66.9 (1.80)	66.6 (1.48)	0.9
Berg Balance Test	51.8 (0.79)	52.5 (0.41)	0.79
Timed Get up and Go (s)	8.9 (0.69)	7.9 (0.28)	0.13

Values are mean (1 SEM).
P compares means in the two groups and, unless otherwise indicated, is based on *t*-test or chi-square (*).

After eligibility was determined, participants were instructed to stand upright and as still as possible, hands crossed behind their back and barefoot on a force platform, eyes closed (blindfolded) condition. Because feet placement was found to influence postural sway (Melzer et al., 2004), subjects were instructed to adopt a standardized narrow base stance with their heels and toes touching. Ten 30-second quiet-standing trials were obtained from each participant. Rest was provided as needed. Center of pressure (CoP) and ground reaction force data during quiet-standing trials were collected with a Kistler 9287 force platform (Kistler Instrument Corp., Winterthur, Switzerland). The force platform data were sampled at a frequency of 100 Hz.

ML-CoP sway range in narrow base stance was used in the sample size estimation. ML-CoP sway range reflects unsteadiness in balance control between fallers and non-fallers (Melzer et al., 2004) and among age groups and test conditions (Raymakers et al., 2005). Twenty subjects would be required to detect a two-sided difference in ML-CoP sway range between old fallers (3.9 (1.0)) and non-fallers (4.7 (1.2)) (Melzer et al., 2004). A significance level of 0.05 and 80% power was chosen for a clinically meaningful estimate. Work by Tinetti et al. (1993) has shown that 30% of individuals over 65 years and almost 50% of individuals over 80 years experience at least one fall each year. Consequently, by recruiting a sample of 100 subjects older than 65 years of age we would likely include at least 30 fallers in the study, allowing a statistical comparison of balance-related parameters between elderly fallers and non-fallers.

2.1. Data and statistical analyses

Stabilogram-Diffusion Analysis, as described by Collins and DeLuca (Collins and De Luca, 1993, 1995; Collins et al., 1995) was performed on the CoP trajectories using a program written in MatLab (Math Works Inc., Cambridge, MA, USA). The current analysis was focused on mediolateral short-term and long-term effective diffusion coefficients (D_{xs} and D_{xl}, respectively), which reflect effective stochastic activity of open-loop and closed-loop postural control mechanisms in the ML direction, respectively. They are derived from the slopes of the short-term and long-term regions of a linear Stabilogram-Diffusion plot. Additional measures of postural sway included the range of the CoP trajectory in the anterior–posterior (AP) and ML directions, mean velocity (i.e., average speed of CoP along its path), and mean sway area (i.e., the area of an ellipse that includes the CoP points during the trial). Values are reported as the average over all ten trials.

To determine differences between groups, independent *t*-test was performed for detection of differences between fallers and non-fallers in short-term (D_{xs}) and long-term (D_{xl}) ML diffusion coefficients as well as critical time (Ct_x) and critical displacement (Cd_x) in the ML direction. An independent *t*-test was also performed on the SDA parameters in AP direction: the effective diffusion coefficients (D_{ys} and D_{yl}), critical time (Ct_y), and critical displacement (Cd_y). Additional *t*-tests were performed on the postural sway parameters (average of ML-CoP range and AP-CoP range, average of trial mean velocities, and mean sway area). Significance levels were adjusted with a Bonferroni correction for multiple comparisons ($P=0.05/4=0.0125$). Statistical significance was accepted at $P<0.05$. All data were analyzed using SPSS software (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Stabilogram-Diffusion parameters

Elderly fallers demonstrated significantly greater short-term effective diffusion coefficients (D_{xs}) in the ML direction compared with the non-fallers ($P = 0.006$; Table 2 and Fig. 1). Also, critical (mean-squared) displacement (Cd_x) was greater in fallers (107.8 (11.8)) compared with non-fallers (77.1 (5.6)) ($P = 0.009$). The critical time interval (Ct_x), long-term effective diffusion coefficients (D_{xl}) in the ML direction, as well as all SDA parameters in the AP direction were not statistically different between groups.

3.2. Sway parameters summary statistics

Statistically significant differences between fallers and non-fallers in average of ML-CoP range ($P = 0.004$) and mean sway area ($P = 0.002$) are shown in Table 2. Average of AP-CoP range ($P = 0.013$) and average of trial mean velocity ($P = 0.019$) were marginally significant after Bonferroni adjustment for multiple comparisons.

4. Discussion

The present study revealed greater short-term postural sway in the ML direction (short-term effective diffusion coefficients (D_{xs})), but not in the AP direction, and greater critical displacement (Cd_x) during narrow base standing, eyes closed condition in elderly fallers compared with older adults with no history of falls. The greater values for D_{xs}, and Cd_x for the elderly fallers suggest an increase in postural sway over short-term intervals in the ML direction for elderly fallers (Table 2 and Fig. 1), indicating postural sway drifting away from an equilibrium point, unchecked by the postural control system (open-loop control). A long-term interval (predominantly closed-loop control) was similar in elderly fallers and non-fallers. This might be an indication of greater sway displacement before closed-loop feedback mechanisms are called into play.

Table 2
Stabilogram-Diffusion and traditional sway parameters for fallers and non-fallers.

	Fallers $N = 29$	Non-fallers $N = 69$	P
Stabilogram-Diffusion parameters mediolateral direction			
Short-term effective diffusion coefficients in $mm^2\ s^{-1}$ (D_{xs})	72.7 (8.9)	50.2 (3.5)	0.006*
Long-term effective diffusion coefficients in $mm^2\ s^{-1}$ (D_{xl})	2.9 (0.5)	2.7 (0.35)	0.7
Critical (mean-squared) displacement in mm^2 (C_{dx})	107.8 (11.8)	77.1 (5.6)	0.009*
Critical time intervals in s (C_{tx})	0.85 (0.28)	1.0 (1.01)	0.23
Stabilogram-Diffusion parameters anteroposterior direction			
Short-term effective diffusion coefficients in $mm^2\ s^{-1}$ (D_{ys})	53.9 (9.8)	37.1 (3.9)	0.055
Long-term Effective diffusion coefficients in $mm^2\ s^{-1}$ (D_{yl})	3.3 (0.5)	3.1 (0.4)	0.56
Critical (mean-squared) displacement in mm^2 (C_{dy})	83.3 (13.2)	58.5 (4.8)	0.03
Critical time intervals in s (C_{ty})	0.72 (1.3)	1.9 (0.3)	0.24
Traditional sway parameters			
Average of ML-CoP range (mm)	43.96 (2.5)	36.7 (1.2)	0.004*
Average of AP-CoP range (mm)	40 (2.3)	34.3 (1.1)	0.013
Average of trial mean velocities ($mm^2\ s^{-1}$)	32.1 (2.1)	27.3 (1)	0.019
Mean sway area (mm^2)	141.3 (13.7)	103.2 (5.4)	0.002*

Values are means (1 SEM).

AP-CoP = anterior–posterior center of pressure, ML-CoP = mediolateral center of pressure.

* Indicates significant differences corrected for multiple comparisons with a Bonferroni adjustment for multiple comparisons ($P = 0.05/4 = 0.0125$).

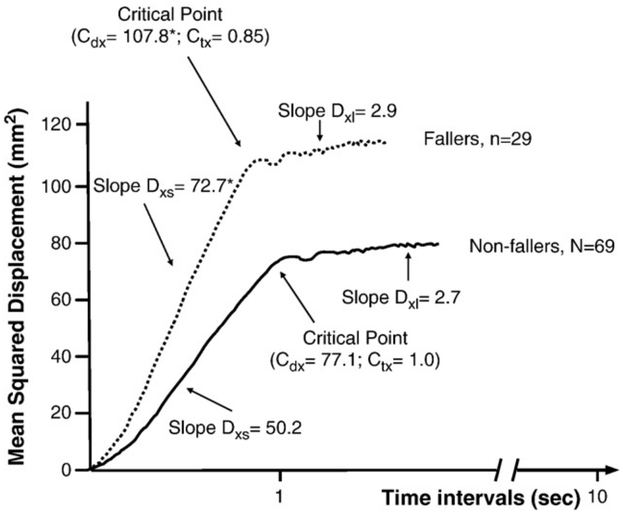

Fig. 1. Stabilogram-Diffusion plot. Experimental mediolateral linear–linear Stabilogram-Diffusion plots for older fallers (dotted line) and older non-fallers (solid line). The computed short-term and long-term diffusion coefficients (in units of $mm^2\ s^{-1}$) are shown for each group. Values are means (1 SEM). The computed critical point coordinates of fallers are: $C_{tx} = 0.85\ (0.28)$ s and $C_{dx} = 107.8\ (11.8)\ mm^2$, and for non-fallers: $C_{tx} = 1.0\ (1.01)$ s and $C_{dx} = 77.1\ (5.6)\ mm^2$. Significant differences ($P < 0.0125$) between older fallers and older non-fallers are indicated by asterisk (*).

Laughton et al. (2003) did not detect any differences in sway behavior between fallers and non-fallers during wide base stance, which may indicate that differences in postural control passed undetected. Under narrow stance and eyes closed conditions, however, the task becomes more challenging (e.g., the subject is less stable) and a more rigid ML control must take place by the postural system, a degree of control that may increase the sway over short-term intervals in the ML direction for elderly fallers. Thus, to reveal weaknesses in the postural control system that may indicate increased fall risk, narrow stance eyes closed condition should be used for clinical testing of balance function. In a different study, Schiffman et al. (2006) found that postural instability increases in the ML directions for the short-term time intervals only with the more challenged stance condition (i.e., additional weight of an external load placed in the backpack). Laughton et al. (2003) reported SDA values in the AP direction only, $Cd_y = 60\ mm^2$ in fallers, less than fallers ($Cd_y = 83\ mm^2$), similar to the value for non-fallers ($Cd_y = 58.5\ mm^2$) we found in the present study. This might be due to the increased difficulty of the task (e.g., narrow stance width and eyes closed) in our study.

Collins and De Luca (1993) and Laughton et al. (2003) suggested that age-related (elderly vs. young) increases in postural sway during short time intervals were due, in part, to an age-related increase in muscle activity (e.g., tibialis anterior, soleus, vastus lateralis, and biceps femoris) during quiet standing, and such activity is correlated with short-term postural sway. Similarly, Benjuya et al. (2004) found age-related changes in the postural control system where older individuals showed increased levels of muscle co-activity, especially across their ankle joints, compared with the young. The force output of skeletal muscle contains noise-like fluctuations (De Luca et al., 1982), which increase with increased muscle activity (Galganski et al., 1993). Although EMG activity was not measured in the current study, our results may be interpreted as an increase in hip abductor muscle activity on both sides in elderly fallers to control postural stability on the ML direction. This co-activation could lead to an increase in short-term ML postural sway, which may compromise the ability to maintain upright stability in narrow base stance. Greater co-activation may be due, in part, to compensation for a decrease in lower limb muscle strength and power (Laughton et al., 2003). Studies have shown a reduction in lower limb muscle mass associated with a reduction in force-generating capacity (Hughes et al., 2001) and an increase in muscle co-activation during standing (Laughton et al., 2003; Benjuya et al., 2004) with increasing age. Thus, weakness in lower limb muscle groups could potentially impair an individual's ability to correct a shift in the body's center of gravity to effectively prevent a fall. Moore et al. (2005) found that immediately after exercise where muscles are fatigued and weaker, postural control was reduced. This was represented by a shift of the critical point to the right (i.e., increased critical time interval), indicating an increase sway in the open-loop control. Laughton et al. (2003) suggested that maintaining muscles in an activated state, thereby increasing muscle co-activation, is an attempt to increase stability under conditions of muscle weakness. Similarly, loss of giant pyramidal inhibitory cells (Betz cells) in the motor cortex, not an uncommon finding in elderly individuals, can also lead to co-activation (Scheibel, 1985). In a recent study Novak et al. (2009) found that white matter hyperintensities (WMHs), which have been related pathologically to neuronal loss in fronto-temporal and parieto-occipital regions in older adults, affected both amplitude and dynamics of postural sway, resulting in smaller and more random (less correlated) fluctuations.

Another explanation for increased muscle co-activation given by Laughton et al. (2003) suggests that an increased level of muscle activity may enhance joint proprioception by increasing the firing rate during the short-term intervals and recruitment of primary afferents, thereby compensating for the function associated with critical displacement (i.e., before closed-loop feedback mechanisms are called into play). This is relevant because Winter et al. (1998) showed that ankle angular velocity displacements during quiet standing were well below the thresholds in the AP direction reported by Simoneau et al. (1996) and were slightly above the AP proprioceptive thresholds reported by Fitzpatrick and McCloskey (1993). Thus, reactive muscle co-activation might be a strategy of increasing proprioceptive input.

In the current study we intentionally increased the difficulty of the task of quiet stance by narrowing stance width and occluding vision. Thus greater reliance on somatosensory input was needed. The data suggest that elderly fallers may be less able to compensate for the loss of visual input through reweighing vestibular and somatosensory information during a challenging balance task. It is well-documented that increased age is associated with an increase in sensory detection thresholds, a decrease in nerve conduction velocity (Wang et al., 1999), and central processing capacity (Melzer and Oddsson, 2004). It is conceivable that these factors could cause postural sway to drift away from an equilibrium point, unchecked by the postural control sensory system increases in short-term quiet stance sway before closed-loop feedback mechanisms are called into play. This would indicate the importance of somatosensory information for postural control during quiet stance. Previous work would support this notion. Melzer et al. (2004) showed a significant decrease in nerve density of the slowly adapting receptor system in the feet of elderly fallers compared with non-fallers (in Two-Point Discrimination 14.93 (1.1) mm vs. 12.98 (0.3) mm, respectively). This suggests that elderly fallers may be less able to detect movement of the CoP under the soles of their feet.

In addition, the experimental modeling work by Peterka (2000) has demonstrated that a simple closed-loop control model of upright stance can generate realistic SDA AP sway parameters. In Peterka's model (2000), increases in short-term sway occurred when the damping factor (the corrective torque generated in proportion to body sway or velocity) was decreased, or when the time delay due to sensing, transmission, processing, and muscle activation was increased. Such SDA changes could occur also in the ML sway parameters in elderly fallers in narrow base stance conditions, with decreased hip muscle strength or with a decline in nerve conduction speed, both of which have been shown to occur with increasing age.

In conclusion, short-time ML postural sway during narrow base standing, with no visual input (e.g., D_{xs} and Cd_x), can effectively and successfully reveal postural control mechanism declines associated with falls in the elderly. However, this study has several limitations. First, the retrospective design of the study provides weaker empirical evidence than prospective studies since older adults may under-report falls or not recall minor fall events. Second, the data came from a fairly small sample that was drawn from a defined relatively healthy community-based population; these results cannot be generalized to extremely weak or institutionalized elderly persons. Third, narrow stance might have low external validity, as older adults do not naturally stand with a narrow base. We, however, claim that older adults do not naturally stand with a narrow base because they prefer a less challenged "safer" posture. Further study should involve larger sample sizes, prospective designs, and less healthy populations of older adults.

Conflict of interest statement

There are no conflicts of interest to disclose for any of the authors.

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