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Stiffness Control of Balance during Dual Task and Prospective Falls in Older Adults: The MOBILIZE Boston Study

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Abstract

Outdoor fallers differ from indoor fallers substantially in demographics, lifestyle, health condition and physical function. Biomechanical predictors of outdoor falls have not been well characterized. Current validated measures of postural deficits, which describe only the overall postural behavior, are predictive of indoor falls but not outdoor falls. We hypothesized that a model-based description of postural muscle tone and reflexes, particularly during dual tasking, would predict outdoor falls. We tested whether postural stiffness and damping from an inverted pendulum model were predictive of future indoor and outdoor falls among older adults from the MOBILIZE Boston Study. The center of pressure data during standing were obtained from 717 participants aged 77.9 ± 5.3 years. Participants stood barefoot with eyes open for 30 seconds per trial, in two sets of five standing trials. One set included a serial subtractions task. Postural stiffness and damping values were determined from the postural sway data. After the postural measurements, falls were monitored prospectively using a monthly mail-in calendar over 6-36 months. Associations of postural measures with fall rates were determined using negative binomial regressions. After covariate adjustments, postural stiffness ($p=0.02-0.05$) and damping ($p=0.007-0.1$) were associated with lower outdoor falls risk, but not with indoor falls. Results were invariant by direction (anteroposterior versus mediolateral) or by condition (quiet standing versus dual task). Outdoor fall risk may be tied to postural control more so than indoor falls. Dual tasking is likely related to fall risk among older and sicker older adults, but not those relatively healthy.

Keywords

Postural control; Falls; Dual task; Motor control; Mathematical model

1. Introduction

Outdoor falls have been recently recognized as a distinct outcome that occurs in otherwise healthy older adults with a different risk profile [1-3]. Although many factors influence fall risk, falls are ultimately mechanical events due to the failure of the postural control system in managing hazards. Although the role of the postural system in managing fall risk is well known [4, 5], measures of postural sway and velocity predict the falls that occur indoors, but not those outdoors [6]. The traditionally descriptive measures of balance performance based on functional tests [7] and the quiet standing postural sway do not predict outdoor falls [2, 3, 6].

One explanation for outdoor falls in seemingly healthy people may be that these individuals have subtle balance problems that are undetected by existing balance tests. Cognitive distractions lead to impaired postural control, especially in older adults with various cognitive impairments. Some have proposed that measuring balance function during a cognitive distraction, using dual-task paradigms, may reveal balance deficits not apparent otherwise [8, 9]. Postural function during a dual task may reveal these subtle balance problems that may lead to outdoor falls, yet no consensus exists on whether measuring balance function with dual task adds to the prediction of falls [10].

Another reason that may be that currently validated predictors for indoor falls are measures of overall behavior, and are not designed to assess the specific functions of the postural control system. Thus, metrics based on the mechanisms of postural control and their response to perturbations may better explain outdoor fall risk.

To that end, we considered a simple biomechanical model of standing postural control, where posture is hypothesized to be controlled by maintaining mechanical stiffness in a damped-oscillator inverted pendulum model [11, 12]. These observed mechanical stiffness and damping describe the capacity to respond to perturbations, reflecting muscle tone, active reflexive and anticipatory control mechanisms [13-15]. Previously we demonstrated that cognitive distractions modify postural stiffness and damping during standing [12]. We hypothesized that greater stiffness and damping in the postural system would be associated with lower risk of falling, particularly outdoors.

To test these possibilities, we prospectively determined the association of postural stiffness and damping from the inverted pendulum model of postural control with the risk of indoor and outdoor falls in a representative cohort of community-dwelling older adults. We also tested whether postural stiffness and damping measured during a dual task paradigm predicted outdoor falls better than those during quiet standing.

2. Methods

2.1 Subjects

The MOBILIZE Boston Study (MBS), standing for “Maintenance of Balance, Independent Living, Intellect, and Zest in the Elderly of Boston” is a prospective study examining risk factors for falls[16]. The study includes a representative population sample of 765 older adults age 70 or above from the Boston area. Inclusion criteria required subjects to be community dwelling, able to walk 6m and communicate in English. Those with cognitive impairment (MMSE < 18) [17], a terminal disease, or severe hearing or vision loss were excluded. After providing informed consent as approved by the Hebrew SeniorLife Institutional Review Board, all subjects underwent a standardized evaluation. A full description of the study design and the collected data are presented elsewhere [16]. Of the 765, falls data were used from 717 subjects who had at least 6 months of falls follow up and were able to stand on a balance platform for 30 seconds.

2.2 Balance Assessment

Participants stood barefoot with eyes open on a force platform (Kistler 9286AA), with the feet about 0.3 m apart. No visual target was specified. The center of pressure (COP) excursions under their feet, in both anteroposterior (AP) and mediolateral (ML) directions were recorded at 240 Hz. Two sets of five standing trials, 30 seconds each, were performed, with one set including a dual task challenge. The order of the two sets was randomized. Trials were grouped by sets of 5 to minimize carryover effects between conditions. COP and force signals were sampled at 240 Hz then low pass filtered with a cutoff of 60Hz [18] using a 7th order Butterworth zero-lag digital filter in MATLAB.

For the dual task challenge, each participant was asked to count backwards out loud by 3 from 500 during each trial (serial-3 subtraction). Participants were instructed to prioritize standing and look forward. In subsequent dual task trials, subjects started the subtractions where they left off in the previous trial. If subjects made 5 errors, the test was modified to counting backward by 1 from 500. If subjects still made 5 errors on this modified task, the task was switched to counting backward by 1 from 100. If subjects still failed this task, they were then asked to name items found at a supermarket. This protocol was conducted to provide a similar amount of performance difficulty to all participants. Participants sat to rest for one minute between trials.

2.3 Postural Model Parameters

The postural system was modeled as an inverted pendulum with rotational stiffness and damping. These parameters were calculated from the COP data using methods described by Winter et al. [11, 12]. Feedback models could not be fit to quiet standing data [19-21] as they require mechanical perturbations. Movements of the center of mass (COM) were estimated using the zero-point-to-zero-point double integration technique, the most concordant with the full-body motion capture based estimates [22, 23]. Fourier transform of the difference between COP and COM (i.e., trembling component of COP[24]) showed an amplitude spectrum $A(\omega)$ consistent with a damped oscillator [11], which was fit to the following function using a least-squares optimization:

$$A(\omega) = \frac{C}{\sqrt{1 + \left[\frac{I\omega}{B} - \frac{K_e}{\omega B} \right]^2}} \quad [1]$$

where C is a scaling constant, I is the moment of inertia of the body about the ankle [25], K_e is stiffness [Nm/rad], B is damping [N-m-s/rad], and ω is the angular frequency (radians/sec). Trials with the model fit of $R^2 < 0.6$ or otherwise poor fits were discarded ($< 1\%$) for quality control. RMS amplitude of the center of mass (COM) sway (COM_{RMS}) was also determined, as the movement of the COM (or rambling component [24] of COP) is managed by the nervous system.

To account for confounding by body size, the postural model parameters were scaled to

$\frac{COM_{RMS}}{h}$, $\frac{K_e}{mgh}$ and $\frac{B}{mgh\sqrt{h/g}}$, where m is body mass, h is height and g is 9.81 m/s^2 [26], then log-transformed to attain a normal distribution. We scaled the variables to body size to account for body size effects, instead of using height and weight as covariates in statistical models, because the exact mathematical relationships are known. These variables were calculated using MATLAB 7.4 (Mathworks, Natick MA). The parameters from the five trials were then averaged to determine the predictor variables during quiet standing vs. dual task conditions in AP and ML directions. The effects of dual tasking in these parameters are discussed in detail elsewhere [12].

The inverted pendulum model as developed by Winter et al. is a single pendulum at the ankle [11]. This is a simplification of the multi-segment dynamics during standing posture in both AP and ML directions [27], and based on the evidence that control at multiple joints all work in a single postural feedback scheme [28], we will refer to K_e and B as postural stiffness and damping (rather than ankle joint stiffness). Of note, stiffness describe here in this population of healthy community-dwelling older adults is distinct from motor 'stiffness' or rigidity due to neurological conditions or 'stiff joints' due to osteoarthritic inflammation.

2.4 Falls Assessment

Prospective falls data were collected using monthly mail-in calendars. At enrollment, participants were given the monthly falls calendar and instructed on how to complete and return them to the study center each month. On average, completed fall calendars were obtained from 97% of the cohort. Participants were instructed to mark an "F" on the days that a fall occurred and an "N" for each day that no fall occurred. [7] Participants who fail to return a completed calendar within 10 days of the end of the month were contacted by telephone for the information. For each fall reported, staff conducted a structured telephone interview. The circumstances, location of the fall, injuries sustained, and the presence of any external and internal factors were asked. Falls were defined as unintentionally coming to rest

on the ground or other lower level not as a result of a major intrinsic event (e.g. myocardial infarction or stroke) or an overwhelming external hazard (e.g. hit by a vehicle).[29]. For the reported events that could not be readily identified or characterized as a fall, the MBS investigators adjudicated the event after reviewing the interview information. The falls were categorized into indoor and outdoor falls. Of note, one person can have both indoor and outdoor falls, as two separate outcomes. Falls follow-up data were available for 6-36 months, up to October 31, 2008. Indoor falls included falls in one's own home, someone else's home, other buildings, and other enclosed spaces, including transportation vehicles. Analysis of falls inside the home yielded similar results to falls occurring in other indoor spaces, and thus only falls for all indoor spaces are presented. Outdoor falls included locations outside stairs, garden or yard, sidewalks, streets, curbs, parking lots, and others.

2.5 Conventional Predictors of Falls

We considered multiple clinical characteristics that may be related to falls based on a literature review[2]. They included age, gender, vision (Snellen chart), peripheral neuropathy in the feet, leg strength (1 RM leg press), fall history, gait speed, and Berg balance test [30]. Peripheral neuropathy was defined using Semmes-Weinstein monofilaments (4.1 and 5.6g), as sensing either of the filaments less than three times out of four in either foot. We quantified executive function using the Trail Making Test Part B (TMT-B) [31] and cognitive status using the mini-mental status exam (MMSE) [17]. Activities of Daily Living (ADL)[32] was used to assess disability. Education (self-report of completing high school), and depression using the Center for Epidemiological Studies depression scale, Hopkins revision (CES-D-R) [33] were also assessed using survey instruments. The ability to complete the serial-3 subtractions was also considered as a covariate.

2.6 Analyses and Statistics

The prospective risk of falls was assessed using incident fall rate over the follow-up period as the outcome. Because of the over-dispersed distribution of fall rate, negative binomial regression models were used to determine the incidence rate ratio (RR), the increase in fall rate associated with a particular variable. $RR > 1$ indicate that fall rate increases by a factor of RR for each unit increase in the predictor; $RR < 1$ indicate a decrease with predictor. Negative binomial regression models were devised for analyzing count or rate data (e.g., number of falls for a given period) which takes into account each subject's exposure (observation) time. Models adjusting for the time spent either indoor or outdoor that was estimated using the PASE questionnaire [34] yielded similar results.

We first assessed the bivariate associations of indoor and outdoor falls rates with each of the biomechanical variable (COM_{RMS} , K_e , B) measured in AP and ML directions during quiet standing (QS) and dual task (DT) conditions (Figure 1). We then adjusted the set of clinical variables in the multivariable models (described below). Clinical variables were included as covariates (covariate adjustment) if they were associated with both prospective falls and the biomechanical variable at $p < 0.1$. SAS 9.1 was used (SAS Institute, Cary NC).

Covariates adjusted in the models included: age, sex, race, depression, fall history, gait speed, physical activity, and difficulty with activities of daily living (ADL). In addition, models for indoor falls were adjusted for sensory neuropathy, Berg Balance Test, and incontinence. Models for outdoor falls were adjusted for education, alcohol use, and executive function. Covariates used with indoor falls and outdoor falls are different because the known risk factors for these two types of falls are different [2]. Models using biomechanical variables measured during DT condition were adjusted for difficulty in performing the dual task. These covariates were used simultaneously in the models in order

to test whether the biomechanical variables are predictive of falls independent of previously known fall risk factors.

3. Results

3.1 Fall rates

These community-dwelling older adults were mostly healthy at their baseline assessment (Table 1)[16]. As of October 2008, during 488,464 person-days of follow up, 1244 falls were reported by mail-in calendars. Of these, 539 could be classified as indoor falls and 495 as outdoor falls; information to determine fall location was not available in the rest. Incidence rates were 0.40 per person-year indoor and 0.37 per person-year outdoors. Of the 717 participants, 320 (45%) did not report any falls. 131 (18%) reported only outdoor falls, 137 (18%) only indoor falls, and rest (18%) both types [2]. Of note, COM_{RMS} , stiffness, and damping were not different among these groups, except AP COM_{RMS} ($p=0.015$) was smaller in non-fallers.

Postural model parameters are given in Table 2.

3.2 Indoor Falls

Greater COM_{RMS} was associated with higher indoor falls (RR ranges 1.88-2.67, $p = 0.002$), after accounting for covariates (RR ranges 1.45-1.84, $p = 0.03$) and adjusting for time spent indoors (RR ranges 1.40-1.66, $p<0.05$; Figure 2). Postural stiffness K_e was not associated with indoor falls ($p = 0.15$). Greater damping B in the AP direction was associated with lower rates of indoor falls (RR=0.65, 95% CI=0.42-0.99, $p=0.044$) only after covariate adjustment. Otherwise, the associations with indoor fall rates were similar between AP and ML data, and between QS and DT conditions (Table 3). In multivariate models, female sex [2], depression, activities of daily living (ADL) difficulties, and previous history of falls were also significant predictors of indoor falls ($p < 0.05$).

3.3 Outdoor Falls

In contrast, COM_{RMS} was not associated with outdoor fall rates ($p = 0.09$), similar to previous reports on descriptive COP measures [6]. Greater K_e and B were associated with lower outdoor fall rates, particularly after adjusting for covariates (Figure 3). In multivariate models, male sex [2], depression, ADL difficulties, and previous history of falls also predicted outdoor falls ($p < 0.05$).

4. Discussion

We found that greater postural stiffness and damping, as described using the inverted pendulum model [11, 12], were associated with a lower risk of outdoor falls in a population of community dwelling older adults. Postural stiffness was predictive of outdoor falls; postural sway was predictive of indoor falls; postural damping was predictive of both. Stronger associations were seen with postural model parameters from the ML direction and dual tasking conditions.

To our knowledge, no other measures of postural control or postural sway behavior have been shown to be predictive of outdoor falls. Our results on indoor falls confirm previous work that postural sway amplitudes and velocities are associated with indoor falls, but not outdoor falls [6]. We found that greater stiffness and damping is indicative of decreased risk of outdoor falls and damping is of indoor falls. This decreased risk effect applies to this community dwelling population, but many not to those with Parkinson's disease or other motor rigidity whose increase in postural stiffness may be a sign of greater fall risk. In

addition, we found that measuring postural control during dual task did not improve fall prediction. This may be because the individual changes in stiffness and damping with dual task were small (<1 SD) compared to the population distributions (Table 2), in this relatively healthy community dwelling population of older adults. In patient populations with cognitive or motor deficits, dual-task decrements in postural control may be more predictive of falls. Further study is required in these populations.

Ours is also the first report of a theoretical biomechanical model of postural control whose predictions were tested using prospective falls data in a representative population of older adults. Previous studies of postural control and falls have relied only on clinical balance tests or sway descriptions [6, 35] or were designed as small case-control studies [5, 36]. Our results go beyond previous work that identified the association of overall postural behavior or performance and falls; by testing postural control theory predictions with epidemiological data, we could identify which aspects of the postural control mechanism affect fall risk. Although this model lacks a feedback mechanism, a big limitation [15], but both passive and active control elements were described as lumped parameters [15, 37]. Currently, we lack a method to describe explicit feedback mechanisms based on quiet standing postural data. In future work, it will be necessary to explicitly model the feedback mechanisms in stabilizing upright standing to better explain the role of distractions on fall risk [12].

Mechanically, stiffness and damping describe a system's response to perturbations, and thus we speculate that damping may reflect the ability of the motor system to manage postural challenges. If so, an older person's risk of falling outdoors may be more strongly tied to the ability to manage fall-causing perturbations as more hazards may exist outdoors, while indoor falls are more influenced by other health factors [2, 3]. It is yet unclear whether control of rambling component of COP is tied to indoor falls or trembling component to outdoor falls. The relationship of damping measured during quiet standing to the ability of the motor system to manage postural challenges needs to be further developed [38].

Although laboratory-based measures of the response to perturbations may provide greater insights into postural neurophysiology [39, 40], these measures need validation through prospective studies of falls in real living situations. In contrast, our measurements were made during quiet standing without mechanical perturbations, thus may not represent postural function during an actual fall. Despite these limitations, translating postural neurophysiology from experiments and concepts from postural modeling to studies of fall risk in a population of older adults has allowed the identification of specific postural mechanisms related to fall risk, a big gap in the literature until now [41].

In conclusion, greater postural stiffness and damping from an inverted pendulum model during quiet standing was predictive of less risk of prospective outdoor falls in a community-dwelling population of older adults. Measuring postural measures during dual task did not add to predicting falls in this relatively healthy older population. Further work is necessary to examine whether these findings apply in patient populations and the role of specific feedback mechanisms in fall risk.

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Research Highlights

Inverted pendulum model of posture was validated using falls in older adults

The MOBILIZE Boston cohort of 765 community-dwelling older adults was studied

Postural stiffness and damping are indicative of lower outdoor fall risk

Dual tasking did not improve fall prediction

Outdoor fall risk may depend more on postural biomechanics than indoor falls

Figure 1.

Schematic Diagram of Data Collection, Modeling and Calculations. A: Postural sway (center of pressure) was measured during quiet stance (QS) and dual task (DT) conditions in anteroposterior (AP) and mediolateral (ML) directions. B: Center of mass (COM) movements were calculated and subtracted from COP data, then the Fourier transform (FFT) was calculated. C: The inverted pendulum model dynamics[11] were fit to the data to determine COM_{RMS} , K_e , and B for each measurement condition. D: A sample fall calendar is shown. Participants write when they have fallen and mail the calendar. Reported falls data were compiled into indoor falls and outdoor falls. In the example shown, the participant experienced 2 indoor falls and 1 outdoor falls. E: Negative binomial regression using fall count data, follow-up time (panel D), one of the biomechanical variables (panel C) and covariates was performed using SAS to yield incidence rate ratios (RR).

Figure 2.

Associations of Indoor Fall Rates and Postural Control Parameters. Rate ratios denoting the strength and the direction of the association between biomechanical predictors and fall rates are shown with 95% confidence intervals. If the 95% confidence bar touches the 'null' line of $RR=1$ (i.e., fall rate is the same regardless of the variable), then the predictor is not significantly associated with fall rate at $p = 0.05$). Multivariate models were adjusted for: age, sex, race, depression, fall history, gait speed, physical activity, ADL, neuropathy, Berg Balance Test, and incontinence. DT models were also adjusted for task ability. Each line represents a separate statistical model, using predictor variables (COM_{RMS} : K_e : B) measured in AP and ML directions during QS and DT conditions. Larger COM_{RMS} was associated with greater risk of indoor falls. K_e and B were not associated with indoor fall rates.

Figure 3.

Associations of Outdoor Fall Rates and Postural Control Parameters. Multivariate models were adjusted for: age, sex, race, depression, fall history, gait speed, physical activity, education, alcohol use, TMT-B, and ADL; DT models were also adjusted for task ability. Larger K_e and B were associated with less risk of outdoor falls. COM_{RMS} were not associated with outdoor fall rates.

Table 1
Demographic, Clinical, and Biomechanical Descriptions

	Mean (SD) or N (%)
N	717
Age	77.9 (5.3)
Sex (% Female)	458 (63.9%)
Race (% non-white)	154 (21.5%)
High school graduate	642 (89.5%)
Daily alcohol use	455 (62.8%)
Vision (20/50 Snellen)	61 (8.4%)
MMSE score	27.1 (2.6)
TMT-B (seconds) (n = 679)	141.2 (77.6)
slow gait (0.67 m/s)	83 (11.6%)
fast gait (>1.33 m/s)	41 (5.8%)
Depression (CES-D-R score)	50.5 (9.9)
Urinary Incontinence	293 (40.4%)
Neuropathy	77 (10.7%)
ADL Difficulty	little 103 (14.3%) a lot 44 (6.1%)
Berg Balance Scale 45	90 (12.6%)
Fall history	262 (36.7%)
Dual Task Ability	441 (63%)
Height (m)	1.63 (0.10)
Weight (kg)	74.1 (19.7)
Moment of Inertia	AP: 71.3 (20.4)
I_a (kg- m ²)	ML: 72.1 (20.6)

MMSE: Mini-mental status exam

TMT-B: time to complete Trailmaking Test Part B

CES-D-R: Center for Epidemiological Studies Depression scale, Hopkins revision.

I_a : moment of inertia of the body about the ankle

*Leg press strength from 1 RM (maximum repetition) trial. Leg press data could not be collected from some participants due to various contraindications.

ADL: Activities of Daily Living

Fall history: self-report of any fall in the previous year Dual Task Ability: Ability to complete serial subtractions by 3

Table 2
Scaled Parameters from Biomechanical Model during Quiet Standing and Dual Task

		QS	DT	P
COM_{rms}	AP	0.84 ± 0.31	0.88 ± 0.33	<0.001
	ML	0.42 ± 0.41	0.51 ± 0.43	<0.001
K_e	AP	-0.49 ± 0.42	-0.51 ± 0.47	0.13
	ML	-0.68 ± 0.43	-0.83 ± 0.45	<0.001
B	AP	-0.82 ± 0.26	-0.78 ± 0.31	<0.001
	ML	-1.15 ± 0.27	-1.06 ± 0.31	<0.001

AP: Anteroposterior movements; ML: Mediolateral movements

QS: measured during quiet stance; DT: measured during dual task

COM_{RMS}: RMS amplitude of center of mass (COM) excursions

K_e: mechanical stiffness

B: mechanical damping

Scaled parameters were used in all negative binomial models. Original parameters are given in [12].

P-value based on paired t-test.