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Postural steadiness during quiet stance does not associate with ability to recover balance in older women

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Abstract

Background. Fall risk depends on ability to maintain balance during daily activities, and on ability to recover balance following a perturbation such as a slip or trip. We examined whether similar neuromuscular variables govern these two domains of postural stability.

Methods. We conducted experiments with 25 older women (mean age = 78 yrs, SD = 7 yrs). We acquired measures of postural steadiness during quiet stance (mean amplitude, velocity, and frequency of centre-of-pressure movement when standing with eyes open or closed, on a rigid or compliant surface). We also measured ability to recover balance using the ankle strategy after release from a forward leaning position (based on the maximum release angle where recovery was possible, and corresponding values of reaction time, rate of ankle torque generation, and peak ankle torque).

Findings. We found that balance recovery variables were not strongly or consistently correlated with postural steadiness variables. The maximum release angle associated with only three of the sixteen postural steadiness variables (mean frequency in rigid, eyes open condition ($r = 0.36$, $P = .041$), and mean amplitude ($r = 0.41$, $P = .038$) and velocity ($r = 0.49$, $P = .015$) in compliant, eyes closed condition). Reaction time and peak torque did not correlate with any steadiness variables, and rate of torque generation correlated moderately with the mean amplitude and velocity of the centre-of-pressure in the compliant, eyes closed condition ($r = 0.48$–0.60).

Interpretation. Our results indicate that postural steadiness during quiet stance is not predictive of ability to recover balance with the ankle strategy. Accordingly, balance assessment and fall prevention programs should individually target these two components of postural stability.

Keywords: Accidental falls; Slips and trips; Musculoskeletal equilibrium; Posture; Reaction time; Biomechanics; Aging; Hip fractures; Risk assessment

1. Introduction

Falls are the leading cause of injury and injury-related death in the elderly (Grisso et al., 1991). While risk for falls associates with a variety of sensory, motor, cognitive, and psychosocial variables, it depends ultimately on ability to maintain balance during daily activities, and on ability to recover a stable upright stance following loss of balance. The former is often characterized by measuring postural steadiness during quiet stance, while the latter is assessed by measuring the individual's response to a sudden external force or displacement of the support surface.

It remains unclear, however, whether ability to maintain balance and ability to recover balance are governed by similar motor and sensory variables, and whether

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performance in one of these tasks is predictive of performance in the other. On the one hand, previous studies have found little association between postural steadiness during quiet stance and ability to recover balance following a postural perturbation (Maki et al., 1990; Owings et al., 2000). This may be due to fundamental differences in the neuromuscular demands of the tasks, including the level of muscular effort involved, the utilization of anticipatory versus reactive postural control strategies, and in the utilization of information from visual, vestibular, and somatosensory systems. On the other hand, previous comparisons have been complicated by fundamental differences in the mechanics of the balance tasks. In particular, while quiet stance is dominated by "feet-in-place" strategies (Gatev et al., 1999), researchers who have examined the association between postural steadiness and ability to recover balance have commonly used balance recovery tasks that involve stepping (Owings et al., 2000). While stepping is a common technique for recovering balance, clearly there are a variety of situations where humans rely primarily on feet-in-place responses to recover balance (such as being nudged in a crowd, standing on a bus that suddenly accelerates, or losing balance while turning or reaching).

Therefore, our goal in the current study was to determine whether there is an association among older women between variables related to postural steadiness and ability to recover balance, when the two task are similar in their kinematics (and thus should be governed by similar muscle groups and sensory organs), but differ in terms of the absence or presence of a postural perturbation. To address this question, we conducted experiments with 25 elderly women to quantify postural steadiness during quiet stance and ability to recover balance using the ankle strategy after sudden release from a forward leaning position. We then used correlation to determine the association between these two components of postural stability.

2. Methods

2.1. Subjects

Twenty-five community-dwelling elderly women (mean age = 78 yrs, SD = 7 yrs) participated in the study. All subjects were recruited from an education-based fall prevention program that operated in local seniors centres, and reported at least one fall in the 18 months prior to their participation in our study.

Subjects were initially interviewed and excluded if they had conditions that would prevent them from performing the experiments, or possessed known risk factors for falls or balance impairments (Lord et al., 1995). These included inability to stand unassisted for 10 min, terminal illness, blindness, Parkinson's disease, stroke, peripheral neuropathy, vertigo or dizziness, and use of psychotropic medications. Subjects were excluded after an on-site evaluation if they had moderate to severe dementia indicated by a Mini Mental State Exam score less than 21 (Folstein et al., 1985), Snellen visual acuity score with corrective lenses worse than 20/15 at 5 ft, gross instability when standing on foam with eyes closed, or impaired big toe position sense or monofilament sensation on the dorsum of the foot. Each subject provided informed written consent, and the experiment was approved by the University Research Ethics Board at Simon Fraser University.

2.2. Balance recovery experiment

We used a tether release protocol (Robinovitch et al., 2002) to measure subjects' ability to recover balance. In these trials, the subject stood on a force plate with her feet approximately shoulder-width apart and arms crossed against her chest. We used a horizontal tether and chest harness to incline her into a stationary forward leaning position (Fig. 1A). We instructed the subject that, upon release of the tether, she should recover a vertical standing position by contracting the muscles spanning the ankles while keeping the knees and hips fully extended, a technique called the "ankle strategy" (Horak et al., 1989; Nashner, 1976). The heels were allowed to leave the ground. To train appropriate body posture and movement, each subject was given three to six practice trials where she leaned into the tether, allowed it to hold part of her body weight, and returned to an upright vertical stance.

We then measured the maximum lean angle where the subject was able to recover a stable upright stance after the tether was suddenly released (tether release time ~15 ms). The first trials involved small lean angles of ~2°, where the subject could recover easily. We then iteratively adjusted the length of the tether and the corresponding lean angle until we identified the maximum value (with a resolution of 7 mm in tether length, and ~0.3° in lean angle), beyond which the subject could no longer recover balance in at least three of five repeated trials. To increase the unexpectedness of the perturbation, the investigator inserted a random time delay of 1–10 s between receiving a "ready" cue from the subject and the time of release. Before each trial, the subject was instructed to maintain her gaze forward and at eye level on a black X attached to the wall approximately 10 ft in front of her.

Subjects were barefoot during the trials and wore spandex shorts and shirt. Rest breaks of approximately 30 s duration were provided between trials, and 5 min sitting breaks were provided every 10–15 trials. To standardize subject's preparedness for the impending perturbation, we controlled the initial anterior–posterior

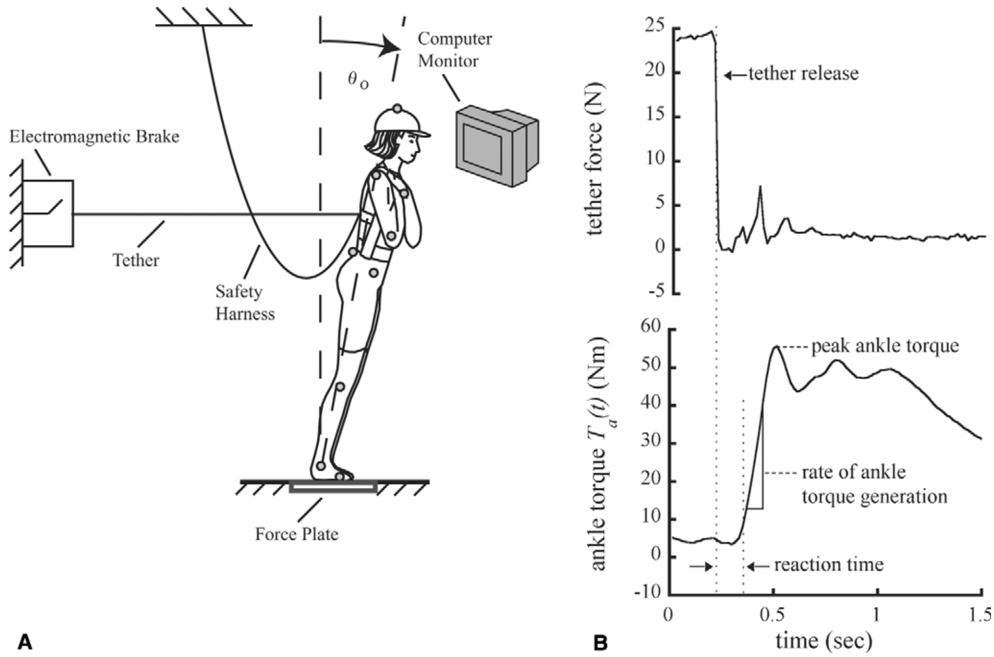

Fig. 1. Balance recovery experiment. (A) Subjects were held by a tether in an initially inclined position and instructed to recover a stable upright posture by contracting their ankle muscles. Their "maximum release angle" (θ_{max}), was the maximum forward lean angle (θ_o) where they could accomplish this task when the tether was released. (B) Measured neuromuscular variables. We detected tether release (shown by the earliest vertical dashed line) by a sharp decline in tether force. Following release, there was a reaction time before the onset of increased ankle torque generation (shown by the second vertical dashed line). Ankle torque was generated at a specific rate, and reached a peak value before declining.

position of the CoP between the feet and ground (an indicator of baseline ankle torque) by instructing subjects to match a target position displayed on a monitor (Robinovitch et al., 2002).

During each trial we measured the magnitude and point of application of foot-floor reaction forces at a rate of 960 Hz with a force plate (model 6090H, Bertec, Worthington, OH, USA). We also measured body segment movements with a 60 Hz, seven-camera motion measurement system (ProReflex, Qualisys Inc., Glastonbury, CT, USA) that recorded the position of 16 markers attached to various anatomical landmarks (see below). The instant of tether release was detected as the onset of a sharp decline in the tension ($\geqslant 2$ N) measured by a load cell (Sensotec, model 31) located in series with the tether.

We calculated the body lean angle $\theta(t)$, defined as the angle from the vertical to a line connecting the midpoint of the two lateral malleolus markers to the midpoint of the two acromion markers (Robinovitch et al., 2002) (Fig. 1A). We also calculated time-varying ankle plantarflexor torque $T_a(t)$ based on the location and magnitude of vertical and horizontal components of foot reaction force (Robinovitch et al., 2002) (Fig. 1B). The baseline ankle torque before release was calculated as the average value of $T_a(t)$ over the 500 ms preceding release.

From each of the three maximum recovery trials, we calculated four outcome variables (Fig. 1B): (a) the maximum release angle (θ_{max}), defined as the average value of $\theta(t)$ over the 500 ms interval preceding tether release; (b) the peak ankle torque generated during balance recovery; (c) the reaction time, defined as the interval between tether release and the instant $T_a(t)$ exceeded baseline ankle torque by 5 N m (always outside baseline variability); and (d) the rate of ankle torque generation following release, defined as the slope of a straight line joining torque–time values at the instant $T_a(t)$ exceeded baseline ankle torque by 5 N m to the instant $T_a(t)$ equalled 85% of the difference between baseline ankle torque and peak ankle torque. The 85% value always reflected a point on the initial smooth rise of the torque–time curve. We normalized values of baseline ankle torque, peak ankle torque, and rate of ankle torque generation by the product of body mass (in kg) multiplied by body height (in m). Values of θ_{max}, peak ankle torque, reaction time, and rate of ankle torque generation used in statistical analyses were averages over three repeated trials for each subject. Among the four variables related to balance recovery ability, we regarded θ_{max} as the primary measure of performance, and the peak ankle torque, reaction time, and rate of ankle torque generation as fundamental contributors to performance.

2.3. Postural steadiness experiment

Each subject also participated in measures of postural steadiness during quiet stance under various support surface and vision conditions. In these measures, the subject was barefoot and instructed to stand "as still as possible" near the centre of a force plate with her feet approximately shoulder-width apart, arms at her sides, and vision directed straight ahead (Fig. 2A). Trials were acquired with the subject standing on the rigid ground with her eyes open (R/EO), and on a compliant surface (open cell foam rubber measuring 42 cm × 31 cm × 10 cm with density 44.1 kg/m^3) with her eyes closed (C/EC). The R/EO condition allowed for full sensory information from visual, somatosensory, and vestibular systems. In the C/EC condition, deprivation of visual and somatosensory information forced subjects to rely more strongly on vestibular information and thus provided a more challenging balance task (Woollacott et al., 1986). Trials were 15 s in duration and a rest break of approximately 30 s was provided between conditions. The R/EO trial always preceded the C/EC trial.

We calculated four measures of postural steadiness from the CoP data in each of the anterior–posterior (AP) and medial–lateral (ML) directions, using formulae provided by Prieto et al. (1996) (Fig. 2B). These were peak-to-peak range of sway distance (RANGE), root mean square distance of sway from the mean CoP location (RMS), mean velocity of sway (MVEL), and mean frequency of sway (MFREQ) (Prieto et al., 1996; Maki et al., 1990). Following Prieto's method, we calculated MFREQ based on the ratio of the mean velocity to the mean distance of sway. MFREQ (in the AP or ML direction) represents the frequency, in Hz, of a sinusoidal oscillation having an average amplitude equal to the mean absolute CoP distance (in the same direction), and a total path length equal to the total excursion of the CoP (again, in the same direction).

In all trials, we used a force plate (model 6090H, Bertec, Worthington, OH) to measure (at 540 Hz) the position of the CoP between the feet and the ground. The CoP time series were then filtered using a recursive fourth order Butterworth low pass filter with 5 Hz cut-off frequency, and the AP and ML components were computed.

2.4. Data analysis

After confirming normality of data by visually inspecting histograms and evaluating one-sample Kolmogorov–Smirnov coefficients, we used Pearson product moment correlation coefficients to test for association between balance recovery variables and postural steadiness variables. A total of five data points (and no more than one for a given variable) from the postural steadiness data were identified as outliers (defined as values >3SDs above or below the mean) and removed before statistical analyses were conducted. All analyses were conducted with statistical analysis software (SPSS 11.0) using a level of significance of $P < 0.05$.

Four subjects were unable to complete the C/EC condition without opening their eyes or using the support of an experimenter's hand. Data from these four subjects were removed from the analysis of the C/EC condition. Furthermore, equipment malfunction prevented us from recording the postural steadiness data from one subject. Data from this subject were excluded, yielding a final sample size of $n = 24$.

3. Results

We observed a considerable range in both balance recovery and postural steadiness variables (Table 1). In line with previous research, the amplitude (RANGE, RMS), velocity (MVEL), and frequency (MFREQ) of CoP sway tended to be larger during quiet stance on the compliant surface with eyes closed than on the rigid surface with eyes open, and in the anterior–posterior than the medial–lateral direction.

Balance recovery variables were not strongly correlated with postural steadiness variables. Maximum

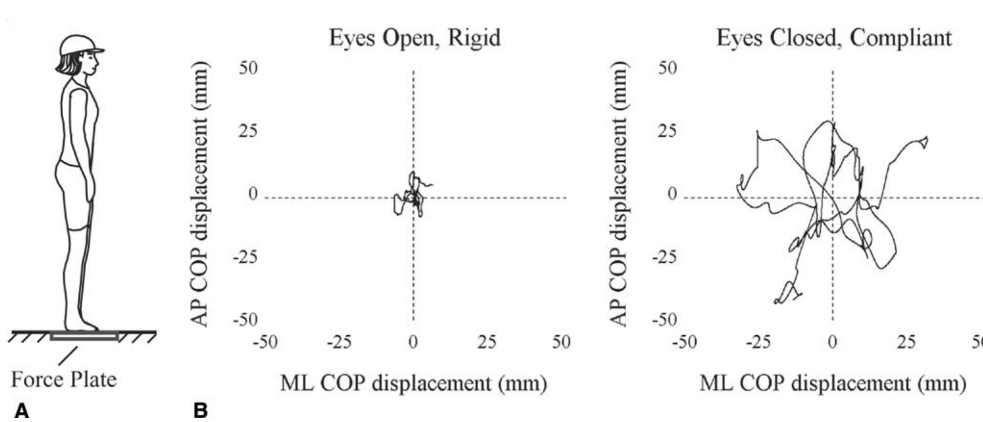

Fig. 2. Postural steadiness experiment. (A) Subjects were instructed to stand "as still as possible" for each trial. (B) The stabilogram from one subject for quiet stance on a rigid surface with eyes open (left trace) and for quiet stance on a compliant surface with eyes closed (right trace). The x-axis indicates sway of the CoP in the medial–lateral (ML) direction. The y-axis indicates sway of the CoP in the anterior–posterior (AP) direction.

Table 1
Means and standard deviations for postural steadiness and balance recovery variables

	Rigid surface eyes open (R/EO)	Compliant surface eyes closed (C/EC)
	Mean (SD)	Mean (SD)
Postural steadiness		
RANGE-AP (mm)	17.0 (6.2)	66.4 (19.4)
RANGE-ML (mm)	8.8 (4.9)	54.8 (26.9)
RMS-AP (mm)	3.6 (1.2)	15.0 (4.8)
RMS-ML (mm)	2.2 (1.4)	12.1 (5.5)
MVEL-AP (mm/s)	6.3 (1.7)	39.4 (14.5)
MVEL-ML (mm/s)	4.3 (2.2)	23.0 (12.8)
MFREQ-AP (Hz)	0.43 (0.14)	0.62 (0.20)
MFREQ-ML (Hz)	0.50 (0.23)	0.42 (0.12)
Balance recovery		
Maximum release angle (deg)	4.77 (1.69)	
Maximum lean angle (deg)	7.39 (1.89)	
Reaction time (ms)	125 (13)	
Peak ankle torque (N m/(kg m))	0.95 (0.16)	
Rate of ankle torque generation (N m/(kg m s))	5.40 (1.81)	

Notes: AP = anterior–posterior, ML = medial–lateral.

release angle (θ_{max}) was significantly correlated with only three of the sixteen postural steadiness variables (Table 2, Fig. 3): MFREQ-AP in the R/EO condition ($r = 0.36$, $P = .041$), RMS-ML in the C/EC condition ($r = 0.41$, $P = .038$), and MVEL-ML in the C/EC condition ($r = 0.49$, $P = .015$). Reaction time and peak ankle torque during balance recovery were not significantly associated with any postural steadiness variables. Rate of ankle torque generation was moderately correlated with RANGE, RMS, and MVEL of postural sway in the AP and ML directions in the C/EC condition ($r = 0.48$–0.60), as well as with RMS-AP in the R/EO condition ($r = -0.42$, $P = .019$).

4. Discussion

In this study with community-dwelling elderly women who had a history of falls, we found little association between variables representative of postural steadiness during quiet stance and ability to recover balance with the ankle strategy. Our results are consistent

Table 2
Correlation between postural steadiness variables and balance recovery variables

	Maximum release angle		Reaction time		Peak ankle torque		Rate of ankle torque generation	
	r	*P*	*r*	*P*	*r*	*P*	*r*	*P*
Rigid surface, Eyes Open (R/EO)								
RANGE-AP (mm)	0.07	.378	0.18	.197	−0.16	.229	−0.34	.055
RANGE-ML (mm)	−0.02	.472	0.01	.483	−0.11	.312	0.02	.472
RMS-AP (mm)	−0.14	.260	0.15	.237	−0.25	.119	−0.42	.019*
RMS-ML (mm)	0.20	.175	0.00	.500	−0.04	.424	0.00	.494
MVEL-AP (mm/s)	−0.22	.159	0.06	.400	−0.31	.078	−0.25	.121
MVEL-ML (mm/s)	0.12	.285	0.07	.370	−0.04	.423	−0.06	.387
MFREQ-AP (Hz)	0.36	.041*	−0.09	.344	0.22	.147	0.26	.114
MFREQ-ML (Hz)	−0.23	.146	−0.10	.323	0.02	.463	−0.07	.374
Compliant Surface, Eyes Closed (C/EC)								
RANGE-AP (mm)	0.35	.065	0.09	.359	0.12	.303	0.54	.007*
RANGE-ML (mm)	0.37	.054	0.05	.412	0.17	.232	0.48	.015*
RMS-AP (mm)	0.31	.092	0.10	.333	0.09	.356	0.55	.006*
RMS-ML (mm)	0.41	.038*	0.06	.407	0.21	.192	0.52	.009*
MVEL-AP (mm/s)	0.28	.123	0.22	.182	0.29	.116	0.57	.006*
MVEL-ML (mm/s)	0.49	.015*	0.03	.456	0.35	.063	0.60	.003*
MFREQ-AP (Hz)	0.13	.292	−0.02	.474	0.15	.263	0.37	.057
MFREQ-ML (Hz)	0.29	.114	0.02	.468	0.29	.115	0.26	.146

Notes: AP = anterior–posterior, ML = medial–lateral.
r = Pearson product moment correlation coefficient.
P = significance level.
* Significant correlation at $P < .05$.

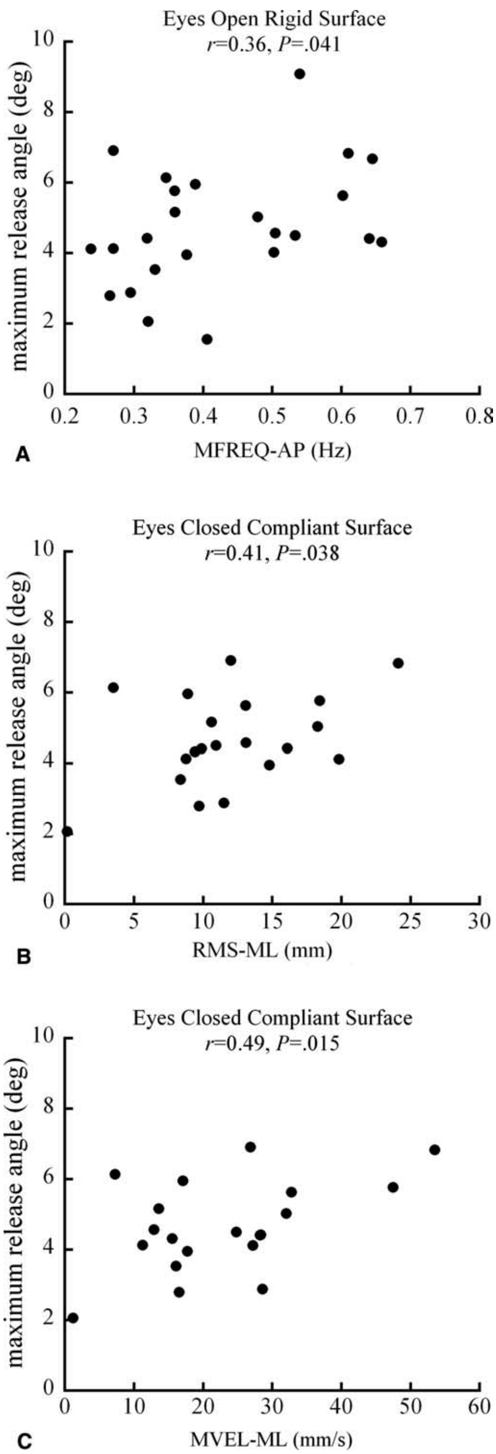

Fig. 3. Significant correlations between maximum release angle and postural steadiness variables. (A) MFREQ-AP during quiet stance on a rigid surface with eyes open, (B) RMS-ML during quiet stance on a compliant surface with eyes closed, and (C) MVEL-ML during quiet stance on a compliant surface with eyes closed.

with, and expand upon, previous investigations of the association between postural steadiness during quiet stance and ability to recover balance following a perturbation. Maki et al. (1990) found that induced sway during continuous platform translations, an index of ability to recover balance after sudden transient platform translations, did not associate with postural steadiness during quiet stance. Furthermore, Owings et al. (2000) reported that neither ability to recover balance with a single step following tether release, nor ability to recover balance after an unexpected trip during gait was associated with postural steadiness during quiet stance.

Despite these previous results, we expected to observe association between our outcome measures, given the similarity in the mechanics of our postural steadiness and balance recovery tasks (neither involved stepping, and both were governed by ankle mechanics). The lack of association may be due to differences in the governing control strategies, and/or the levels of neuromuscular effort associated with the two tasks. In particular, balance control during quiet stance appears to be governed in part by anticipatory strategies (Morasso and Schieppati, 1999; Morasso and Sanguineti, 2002), involving the use of velocity information from somatosensory afferents to modulate ankle muscle activity prior to changes in centre of mass position (Gatev et al., 1999; Masani et al., 2003). In contrast, balance recovery is governed by reactive strategies, triggered by afferent feedback from visual, vestibular, and somatosensory systems in response to the perturbation (Woollacott et al., 1986; Horak et al., 1990). Furthermore, when compared to quiet stance, balance recovery requires closer to maximum values for reaction time, peak ankle torque, and rate of ankle torque generation.

We were surprised to observe that larger values of sway during quiet stance in the eyes closed/compliant surface condition were associated with faster rates of ankle torque generation during balance recovery trials. The exact cause and effect relationship is difficult to identify. One possibility is that subjects who could develop ankle torque quickly were more comfortable withstanding greater amplitudes and velocities of sway, and thus did not control their sway as tightly as subjects who could not generate ankle torque as quickly. Alternatively, subjects who tend to sway more in general may have learned, over time, to compensate by leaning further forward and developing faster rates of ankle torque generation. A similar result was observed by Owings et al. (2000), who found that elderly subjects who could successfully recover their balance after tripping demonstrated faster speeds of lateral CoP displacement during quiet stance than subjects who could not recover successfully.

It is important to consider that our measure of balance recovery ability was the maximum release angle where the ankle strategy could be successfully performed, as opposed to the maximum angle after release i.e., prior to reversing the direction of rotation. This was based on the notion that the maximum release angle represents the largest "perturbation size" where recovery is possible (Robinovitch et al., 2002), and reflects the combined influence on recovery ability of both strength (peak torque) and speed of response (reaction time and rate of torque generation). In contrast, the maximum angle during recovery can be affected differently by strength and response speed, and therefore may be a poor measure of recovery ability. For example, an individual who is strong but slow to respond might have a large maximum lean angle during recovery, but a small maximum release angle. This individual would not possess good recovery ability, but would exhibit a dramatic recovery from a small perturbation.

There are important clinical implications to our results. Specifically, our results support the need to measure both balance recovery ability and postural steadiness in assessing risk for falls in the elderly. While previous studies have shown that postural steadiness during quiet stance is a significant predictor of fall risk, the association is moderate at best (Lord et al., 1994; Maki et al., 1994). It is likely that ability to recover balance provides additional information about fall risk by quantifying the strength and speed with which an individual responds to an impending fall (Patla et al., 1992; Tang and Woollacott, 1996; Amiridis et al., 2003; Maki et al., 1990).

We acknowledge certain limitations of this study. We tested a relatively healthy group of elderly women, so our results may have limited applicability to frailer populations. We also focused on balance tasks involving only the ankle strategy. However, our results are supportive of previous studies comparing postural stability during standing to balance recovery by stepping (Owings et al., 2000). Finally, as with most laboratory-based measures of balance recovery, there may be important differences between real-life causes of imbalance and the conditions we examined. Of particular note is the fact that our subjects knew that a perturbation (in our case, the tether release) was impending, although they could not predict the exact instant of release. This anticipation may have affected their recovery ability by increasing their mental/physical readiness, and the excitability of involved elements of the neuromuscular system.

In summary, we found that, among community-dwelling elderly women, postural steadiness during quiet stance was not associated with ability to recover balance with the ankle strategy. This reflects that performance on these two tasks is governed by different control mechanisms (anticipatory versus reactive), and that clinical programs for assessing and reducing risk for falls in the elderly need to target both balance maintenance and balance recovery.

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