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Age-Related Differences in Maintenance of Balance During Forward Reach to the Floor

Manuel E. Hernandez,[1,2] James A. Ashton-Miller,[1,3] and Neil B. Alexander[2,3,4]

[1]Department of Biomedical Engineering, Biomechanics Research Laboratory,
[2]Department of Internal Medicine, Division of Geriatric Medicine, Mobility Research Center, and
[3]Institute of Gerontology, University of Michigan, Ann Arbor
[4]Veterans Affairs Ann Arbor Health Care System Geriatric Research, Education and Clinical Center (GRECC), Ann Arbor, Michigan.

Address correspondence to Manuel E. Hernandez, Mobility Research Center, University of Michigan, 2025 Traverwood Drive, Suite E, Ann Arbor, MI 48105. E-mail: manueleh@umich.edu

Background. Downward reaching may lead to falls in older adults, but the underlying mechanisms are poorly understood. This study assessed differences between younger and older adults in postural control and losses of balance when performing a forward reach to the floor in 2 possible real-world situations, with and without full foot contact with the floor.

Methods. Healthy younger (n = 13) and older (n = 12) women reached as fast as possible to a target placed at their maximal forward reaching distance on floor, either standing on their whole foot or on the shortest base of support (BOS) that they were willing to perform a toe touch with.

Results. Compared with younger women, older women used a 50% larger BOS when stooping down to touch their toes and had 22% less maximal forward reaching distance on the floor. Older women were twice as likely to lose their balance as younger women while performing a *rapid* forward floor reach ($\chi^2(2) = 3.9$; $p < .05$; relative risk = 1.91; 95% CI = 0.99–3.72). Postural sway, measured as center of pressure excursions and center of pressure root mean square error, did not differ between younger and older women anteriorly, but posteriorly, older women decreased their sway in full foot BOS and increased their sway in forefoot BOS (Age × BOS, $p < .05$). Leg strength was reduced in older versus younger women and was correlated with maximal reach distance (r = .65–.71).

Conclusions. Healthy older women performing a rapid maximum forward reach on the floor, particularly when using their forefoot for support, are at an increased risk for losing their balance.

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STOOPING, crouching, or kneeling (SCK) movements require significant coordination, muscle control, and balance (1–4). Falls frequently occur while performing activities involving stooping, bending, or reaching movements (5). Thus, it is not surprising that downward reaching tasks, necessitating the use of SCK movements, are often included in clinical fall risk assessments (6,7). Even though difficulty bending down to pick up an object from the floor is associated with increased fall risk in older adults (8), few studies have explored the mechanisms underlying downward reach difficulty (9,10).

The strategies used by older adults to maintain balance while performing common daily activities with large ranges of motion at the trunk or hip (e.g., rising from a chair or ascending and descending stairs) have been examined in previous studies (11,12). When bending down to the floor, both balance and body configuration must be simultaneously coordinated to account for pending interactions with the environment (4,13,14). In addition to differing back and lower extremity mobility requirements (15), crouching may require stronger hip and knee extensors than stooping, although providing decreased whole-body center of mass (COM) displacements useful for maintaining balance (16). Thus, crouching and stooping tasks may provide complimentary information about the functional capacity of older adults. As observed in prior postural control studies (17–19), anteroposterior postural sway and COP excursions can provide reliable measures of balance function in older adults. Thus, evaluation of COP control strategies in downward reaching and upward recovery movements may provide useful insights into age-related changes during these activities.

To our knowledge, no studies have explored the effect of a limited base of support (BOS) on the postural control and performance of functional downward reaching tasks in older adults. This study was designed to assess the effect of aging on the performance of a forward reach to the floor (i.e., forward floor reach). A key experimental parameter was to limit the length of the BOS by having participants stand on their forefoot. This constraint simulates typical downward reaching and leaning tasks when the heel lifts off the ground. Furthermore, a limited BOS constrains leg torque output, thereby simulating the decreased lower extremity strength that might be seen in older adults with SCK difficulty. Decreases in lower extremity strength would be expected to be associated with deficits in functional downward reaching performance measures, particularly for older women, as older women require a greater relative amount of strength to perform functional tasks, in comparison to younger women and older men (20). Furthermore, this study focused on women because they are at higher risk for injurious falls and report more impaired balance than men (21–23).

We hypothesized that in comparison to younger women, healthy older women would exhibit a higher incidence of losses of balance during a forward floor reach. We further hypothesized that during a forward floor reach, decreasing the length of the BOS, from the whole foot to just the forefoot, would lead to a disproportionate decrease in COP control in older women when compared with younger, as evaluated by increased COP excursion and postural sway. Insights from this study may be useful in understanding the balance strategies used by older adults for reaching downward and how these might lead to losses of balance.

Methods

Participants

Thirteen healthy younger (aged 18–30 years) and 12 healthy older women (aged 65 years or older) were recruited from the local community. Most young participants were students at the University of Michigan. Community-dwelling, functionally independent older participants were recruited largely from a database maintained by the University of Michigan Older Americans Independence Center Human Subjects Core. All young women completed a medical history questionnaire and older women were physically screened by a nurse practitioner, in order to exclude those with musculoskeletal or neurological abnormalities. Exclusion criteria included medical instability (eg, chest pain upon exercise, dyspnea, acute infection), severe and frequent back or lower extremity pain, and severe musculoskeletal or neurological impairments that may affect balance or downward reaching mobility (eg, cerebrovascular accident, Parkinson's disease, peripheral neuropathy, joint replacement). Participants wore standardized canvas shoes during all testing to control for the friction coefficients within tests. All participants provided written informed consent as approved by University of Michigan Medical School Institutional Review Board procedures.

Instrumentation

Participants stood on a single ground-level six-channel force plate (OR6-7-1000, AMTI, Watertown, MA) with data collected at a sampling rate of 100 Hz. Kinematic data were collected using a three camera, three-dimensional, motion capture system (two Optotrak 3020 and one Optotrak Certus Camera, Northern Digital, Inc., Waterloo, Canada). Infrared light-emitting diodes were placed on the right leg over the lateral malleolus, heel, fifth metatarsophalangeal joint, femoral epicondyle; greater trochanter; over the right acromion; on the right arm over the humeral lateral epicondyle; ulnar styloid process; third metacarpophalangeal joint; and over the nail of the middle finger. On the left-hand side of the body, markers were placed over the left medial malleolus, heel, first metatarsophalangeal joint, left acromion, and over the nail of the middle finger. In addition, a set of three technical markers were placed over the middle of the left thigh and left forearm to use in estimating joint movements during experimental trials. Kinematic data were sampled at 25 Hz. All data were recorded using the Optotrak system and First Principles software (Northern Digital, Inc., Waterloo, Canada). Isometric peak torque of the knee extensors and ankle plantar flexors and dorsiflexors were evaluated using a Biodex System 3 isokinetic dynamometer (Biodex Medical Systems, Inc., Shirley, NY). Torque data were sampled at a rate of 100 Hz. In addition, passive repositioning errors of the ankle joint were measured using the Biodex System 3.

Protocol

This experiment was part of a larger study and consisted of two test sessions. On the first visit to the laboratory, the testing session included calibration trials to assess participants' maximal forward reaching distance on floor, as well as their minimal BOS at their toes. In addition, participants provided their self-reported balance confidence through the Activities-Specific Balance Confidence Scale (24) and performed strength and passive ankle repositioning error tests. Strength tests were performed as described on a previous study (10). On the second test session, participants performed symmetric two-handed downward reaches to a target placed on the floor. All experimental trials were normalized to the maximal forward reaching distance on floor, which was defined as the distance between the anterior edge of the BOS at an upright stance and the most anterior position of the fingertip at the floor level (Figure 1). Experimental trials were also performed at each participant's forefoot BOS. To establish the forefoot BOS, participants first bent down to touch their toes on a full BOS, with as little knee flexion as possible. Participants then moved posteriorly in quarter inch (0.635 cm) increments until they were unable or unwilling to perform the maximal toe reach. The forefoot BOS was then defined as the minimal distance between the toes and the posterior edge of the platform during a successful maximal toe reach (Figure 2).

Practice downward reach trials were first performed at a comfortable speed, and then followed by trials at a fast speed. Participants were instructed to move "as fast as possible" toward and from a target positioned at the maximal

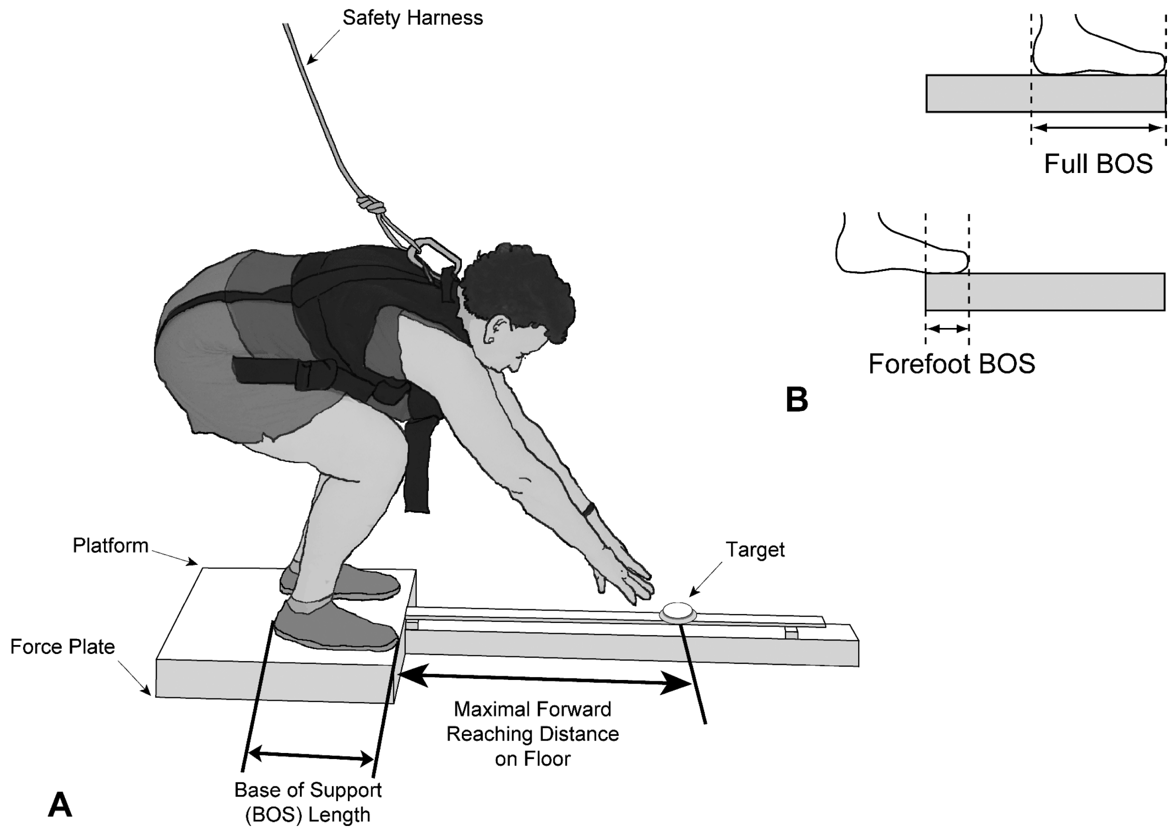

Figure 1. (**A**) Illustration of symmetric two-handed downward reaches to a target placed on the floor under challenging reach conditions. (**B**) Full base of support (BOS) and forefoot BOS conditions used for experiments.

forward reaching distance on the floor, (Figure 2) at a pseudo-randomized BOS condition. Three trials were performed at either full BOS or forefoot BOS.

Data Analysis

Custom Matlab (v7.4, Natick, MA) data processing software routines were used to process the data. Raw force plate data were processed with a fourth-order, zero-lag, low-pass Butterworth filter with a 10-Hz cutoff frequency. COP velocity and acceleration were calculated using a five-point finite difference derivative algorithm. Using an automated procedure, downward reaching and upward recovery movements to an upright stance were calculated for each trial. Marker velocity profiles were used to identify the peak velocity in the downward reach and upward recovery movements. The onset of downward reaching movement was defined by having the software algorithm trace backward from the sample with the peak velocity to locate the first sample at which the velocity exceeded 10% of the maximum value, within the starting zone (25). The end of the upward recovery movement was similarly found by tracing forward from the sample with the peak velocity to identify the first sample less than or equal to 10% of maximum. The transition from the downward reach to the upward recovery movement was identified by the change in overall marker velocity nearest in time to the maximal forward distance or minimal vertical height of the selected marker.

To determine whether the effect of age on the COP control of downward reaching movements becomes more pronounced in tasks with a limited BOS, we examined the incidence of losses of balance, COP excursion, movement time, and number of COP submovements. Analysis of joint motion using optoelectronic cameras provided an assessment of the mean number of losses of balance, defined by the execution of a change in BOS strategy, namely a stepping maneuver, occurring during the downward reach or upward recovery phase of movement. COP excursion was defined by subtracting the mean COP position in a movement from the actual COP position at a given time, and this was used for calculating the minimum posterior and maximum anterior excursion and mean root mean square error. Movement time was defined by measuring the elapsed time from the onset to the offset of a downward reach or upward recovery movement.

Statistics

All statistical analyses were carried out in SPSS 16.0 for Windows (SPSS Inc., Chicago, IL). Independent sample *t* tests and chi-square tests were performed to assess age

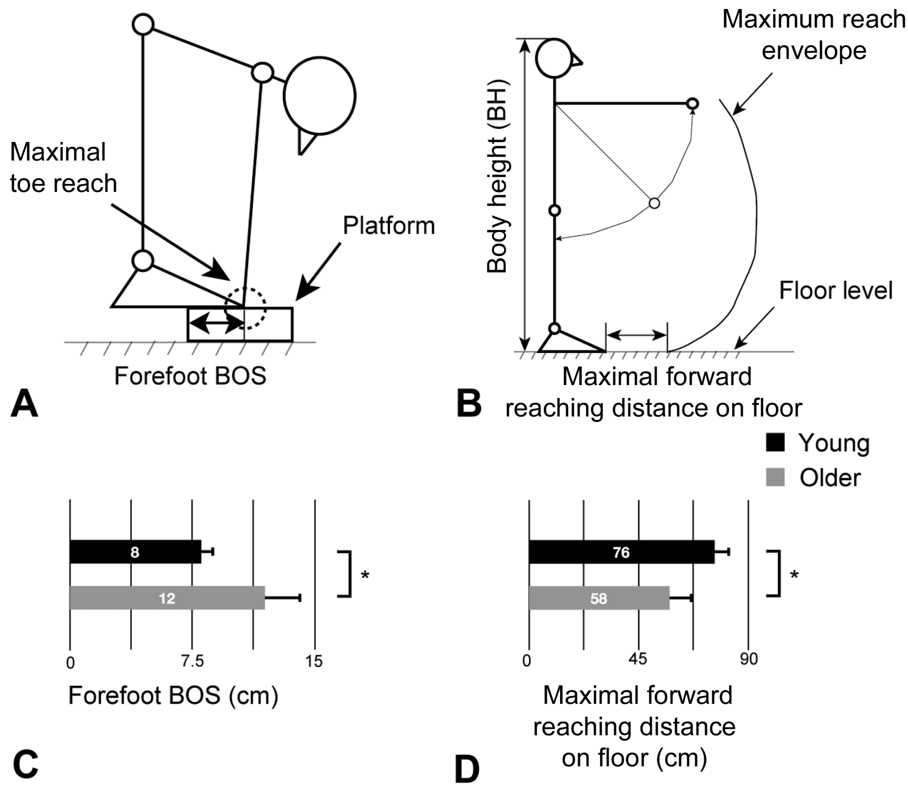

Figure 2. (**A**) Illustration of forefoot base of support (BOS) as defined by the minimal distance between the toes and the posterior edge of the platform during a successful maximal toe reach. (**B**) Maximal forward reaching distance on floor, defined as the distance between the anterior edge of the BOS at an upright stance and the most anterior position of fingertips at the floor level. (**C**) Mean (*SD*) values of forefoot BOS. (**D**) Maximal forward reaching distance on floor. Test results indicated by $^{*}p < .01$.

differences in balance confidence, functional reaching and peak torque performance, and rate of losses of balance during a forward floor reach. The effect of age on functional reaching measures was evaluated using a univariate analysis of covariance (ANCOVA) using body mass index (BMI) and lower extremity strength composite score (ie, a composite score of knee extensor, ankle dorsiflexor and plantar flexor strength using principal component analysis) as covariates. Linear mixed models using a restricted maximum likelihood method were used to examine the effect of age (ie, young vs old), BOS condition (ie, full vs forefoot BOS), and movement phase (ie, downward reach or upward recovery) on outcome measures of postural control. BOS condition and movement phase were identified as repeated effects assuming a first-order autoregressive covariance structure. Within-group and across-group correlations among downward reach performance measures, peak torque performance, and overall loss of balance rate were evaluated using the Pearson correlation coefficient. $p < .05$ was used for statistical significance.

Results

Characteristics of the 25 participants included in this study are presented in Table 1. Older women were shorter than younger women ($p < .05$) but were not significantly different in weight and foot length. There were significant decreases in lower extremity strength in older women, when compared with the younger (eg, knee extensor, ankle dorsiflexor strength, and ankle plantarflexor strength normalized for body height and body weight, $p < .05$; Table 2). However, in comparison with younger women, healthy older women participating in this study reported no statistically significant differences in ankle repositioning error or activities-specific balance confidence score.

Table 1. Mean (SD) Subject Characteristics

	Young Women ($n = 13$)	Older Women ($n = 12$)
Mean age (y)*	23 ± 3	76 ± 6
Height (cm)†	164 ± 6	159 ± 5
Weight (kg)	63 ± 11	63 ± 11
Body mass index (BMI; kg/m^2)	23 ± 4	25 ± 5
Foot length (FL; cm)	26 ± 1	25 ± 3

*Indicates age group effect ($p < .005$).
†Indicates age group effect ($p < .05$).

Downward Reach Performance

Older women demonstrated a 22% decrease in their maximal forward reaching distance on floor in comparison with younger women ($p < .01$). Older women also used a 50% larger BOS, in comparison with younger women, when successfully bending down to touch their toes (ie, forefoot BOS, $p < .01$; Figure 2). After normalizing for body height,

Table 2. Mean (*SD*) Capacity and Downward Reach Performance Measures

	Young Women (n = 13)	Older Women (n = 12)
Capacity		
Knee extensor strength (% BH × BW)*	11 ± 4	7 ± 2
Ankle PF strength (% BH × BW)†	6 ± 2	4 ± 2
Ankle DF strength (% BH × BW)†	2 ± 1	1 ± 1
Ankle repositioning error (deg)	3 ± 2	4 ± 2
Activities-specific balance confidence (0–100 scale)	97 ± 2	96 ± 4
Downward reach performance		
Forward reach movement time (s)	2.3 ± 1.1	2.6 ± 1.2
Maximal forward reaching distance on floor (% BH)†	46 ± 3	36 ± 5
Minimal toe base of support (% FL)†	31 ± 3	46 ± 8

Notes: BH = body height; BW = body weight; FL = foot length; PF = plantarflexor; DF = dorsiflexor.
*Indicates age group effect ($p < .05$).
†Indicates age group effect ($p < .005$).

the maximal forward reaching distance on floor was still significantly decreased in older women versus younger ($p < .005$; Table 2). Similarly, after dividing by foot length, the forefoot BOS remained significantly increased in older women in comparison with younger women ($p < .005$; Table 2). Older women were 16% slower in forward reach movement time than younger women, but the difference was not statistically significant. In univariate ANCOVAs, there were some significant effects seen for the covariates (BMI and lower extremity strength composite score) on downward reach performance measures, but group effects between younger and older women were still significant ($p < .005$). The lower extremity strength composite score was found to have a significant effect on the maximal forward reaching distance on floor ($p < .05$), whereas BMI had a significant effect on forefoot BOS ($p < .01$). Correlations between the forefoot BOS and ankle plantar flexor and dorsiflexor strength were significant across all participants (Pearson's $r = -.50$ to $-.62$, $p < .05$) but not within each group. Significant correlations between the maximal forward reaching distance on the floor and knee extensor, ankle plantar flexor strength, and dorsiflexor strength ($r = .65$–$.71$, $p < .001$) suggest that maximal downward reaching is associated with reduced lower extremity strength capacity in healthy women. The correlations between maximal forward reaching distance on floor and lower extremity strength varied between ($r = .12$–$.46$) within older women and ($r = .44$–$.82$) within younger women. Furthermore, both forefoot BOS and the maximal forward reaching distance on the floor were significantly correlated ($r = .76$, $p < .001$).

Rate of Losses of Balance

During testing, older women lost balance on nearly 31% of trials compared with nearly 17% for the younger women. Chi-square tests suggest that older women lose their balance at higher rates than younger women ($\chi^2(2) = 3.9$, $p < .05$), with a relative risk of 1.91 (95% CI = 0.99–3.72). Significant correlations between normalized knee extensor strength and ankle dorsiflexor strength and loss of balance rate in forefoot BOS trials were observed across groups ($r = -0.43$ to -0.48, $p < .05$). However, within older women, no significant correlations were observed between loss of balance rate in forefoot BOS trials and participant characteristics (i.e., age, height, weight, BMI, foot length) and capacity measures (i.e., lower extremity strength, ankle repositioning error, and activities-specific balance confidence, $p > .05$).

COP Excursion and Postural Sway

COP excursion was quantified through the measure of maximum anterior and minimum posterior COP excursion and the COP root mean square error during downward reach and upward recovery to upright stance. The maximum anterior COP excursion significantly increased in full BOS trials in comparison to forefoot BOS trials, $F(1,41) = 17.9$, $p < .001$ (Figure 3), and during the downward reaching

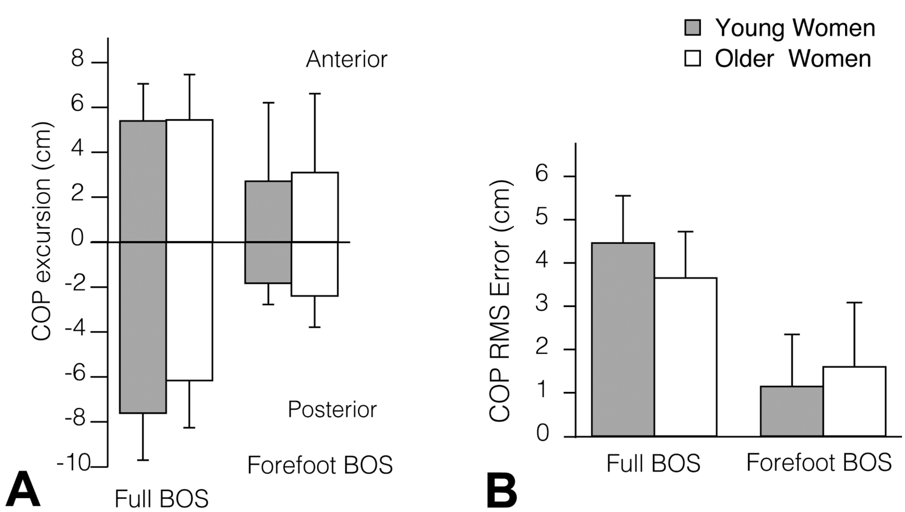

Figure 3. (**A**) Mean (*SD*) maximum anterior or posterior center of pressure (COP) excursion and (**B**) COP root mean square (RMS) error in forward floor reach.

versus upward recovery phase, $F(1,30) = 8.5$, $p < .01$. The minimum COP excursion was smaller in forefoot BOS trials, in comparison with full BOS trials, $F(1,24) = 190.4$, $p < .001$. A significant interaction between age and BOS condition was found, $F(1,24) = 8.6$, $p < .01$, as well as a significant interaction between movement phase and BOS condition, $F(1,50) = 9.5$, $p < .005$. Considering postural sway, as evaluated by the COP root mean square error, significant decreases were observed in forefoot BOS trials versus full BOS trials, $F(1,36) = 112.5$, $p < .001$. Furthermore, an interaction between age and BOS condition was observed, $F(1,36) = 6.4$, $p < .05$. No other significant differences were observed.

Discussion

We present the first data demonstrating that older women have nearly twice the risk of losing their balance than younger women while performing a forward floor reach. This study furthers our understanding of healthy aging and its effect on functional reaching (18,26,27) by examining the effect of a limited BOS during typical reaching and leaning tasks when the heel lifts off the ground. Consistent with prior findings that healthy older women are less able to recover balance than younger women during a forward fall (28), healthy older women had an increased rate of losses of balance despite using a 50% larger BOS and reaching to 22% closer targets during a forward floor reach, in comparison with young. Measures of postural sway and COP excursion have been used as standard assessments of balance capacity in older adults (17,18,23). Consistent with prior leaning literature (17), older women demonstrated increased posterior COP excursions and postural sway than younger women when using a limited BOS.

An exploratory finding was that, across all participants, decreased lower extremity strength was correlated with an increased loss of balance rate when performing a forward floor reach with forefoot support. Reduced lower extremity strength is associated with self-reported SCK difficulty (9,10) and leg strength has also been associated with functional performance (29,30). Older adults require a greater relative amount of effort to perform functional tasks, in comparison with younger adults (31–33). When kneeling, trunk strength is decreased due to a reduced capability to rotate the pelvis backward and change the configuration of the leg (34). Adequate ankle dorsiflexor and plantarflexor strength may be required to generate corrective torques about the ankle to maintain equilibrium by moving the COM forward or backward during stooping movements, due to the limited range of motion at the knee and hip. When crouching down, ankle plantarflexors and dorsiflexors coactivate (33,35). Furthermore, knee extensor strength would be expected to play a significant role in the recovery to an upright stance after crouching or kneeling, given the significant activity seen in thigh muscles during the upward recovery phase (36). Consistent with previous findings (33–35), we observed significant correlations between lower extremity strength and the maximal forward reaching distance on floor. Thus, the limited strength reserves available to older adults (37–39) may contribute to falling while bending down to the floor (5).

Decreasing the BOS from the entire foot to just their forefoot significantly decreased COP excursion and postural sway (ie, COP root mean square error) in both younger and older women, consistent with previous findings (40–43). Compared with the younger, older women used similar anterior COP excursions but tended to decrease posterior COP excursion with the full BOS and increase COP excursion with forefoot support (ie, the interaction of Age × BOS condition), suggesting some limitations in how far posterior COP excursions were allowed in a full BOS and limitations in how tightly posterior COP excursions could be constrained in a forefoot BOS by older women. Similar to postural control studies under perturbations (44), our study demonstrated that healthy older women and younger women differ in their response to imposed disturbances.

Anteroposterior postural sway, as evaluated by the minimum COP excursion also demonstrated a significant interaction between BOS condition and movement phase. The contrast between the downward reach and upward recovery phase may arise from the use of "forefoot BOS" conditions, which allow for the normal use of toe flexor musculature when moving anteriorly but are limited when moving posteriorly, as the heels are not in contact with the raised platform. The constraints on posterior COP movements may be responsible for the similarity in COP control strategies between younger and older women, as the available postural control strategies to reach down to a target and return to an upright stance may be highly constrained.

Difficulty with performing downward reach and upward recovery movements may be indicative of an increased risk of falls among older adults (8), as picking up a slipper from the floor has been found to be a significant task in identifying fallers from nonfallers (45). Existing clinical tests using downward reach and pick-up items have focused on submaximal performance, unlike forward reaching tests (18,46). Even though people usually pick up an object from the floor well within their maximal reach, this study further supports the use of maximal performance measures for downward reach and pick-up tasks, as the maximal forward reaching distance on the floor was found to elicit significant age-related changes, even after accounting for body size and lower extremity strength. Older women have been found to use larger anterior margins of safety than younger women while reaching upward (27), similar to this study's finding of an increased forefoot BOS in older women versus younger women. The increased postural sway seen in older women when standing on a limited BOS, suggests that older adults have more difficulty than the young lifting their heels off the floor for fear they might fall. This observation is in contrast to the commonly used heel-off strategy seen in older adults when crouching and reaching to a target (33) and might underlie the increased fall risk found in older adults with downward reaching difficulty.

The exclusive use of women in this study limits generalizability, as does the excellent health of the older participants. The small sample size is a limitation, as more statistically significant differences may have arisen with additional participants. The inclusion of additional trials would also have been beneficial to this study, to better control for intrasubject variability. The focus on anteroposterior postural control measures limits the scope of this study, as kinematic changes and particularly lateral body motion (47) might provide further insight to the nature of age-related changes. Furthermore, trials in which a loss of balance occurred were not analyzed in this study.

We conclude that healthy older women, when reaching downward and particularly when using their forefoot for support, may alter their balance strategy and are at risk for losing their balance, with reduced lower extremity strength serving as a key contributor. Future studies should further examine kinematic and COM control differences due to aging and their movement phase dependencies in complex whole-body movements, as well as contributing factors to actual losses of balance in downward reach movements.

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