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The relationships between compensatory stepping thresholds and measures of gait, standing postural control, strength, and balance confidence in older women

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Abstract

Background: Compensatory stepping thresholds evaluate the response to postural disturbances. Although such fall-recovery measures are a promising indicator of fall risk, the relationships between stepping thresholds and other measures used to predict falls are not well established.

Research Question: We sought to quantify the relationships between stepping thresholds and other measurements used to assess fall risk in older women, a population at high risk for falls and related injuries, including fractures.

Methods: We studied 112 ambulatory, community-dwelling women, age 65 years or older. Using a treadmill to deliver standing postural disturbances, we determined anterior and posterior single-stepping and multiple-stepping thresholds. These thresholds represented the magnitude of the disturbance that elicited one step or more than one step, respectively. We also assessed balance confidence, functional reach, unipedal stance time, isometric strength, obstacle crossing, postural sway, and gait kinematics. Outcomes were normalized to body size.

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Conflicts of interest statement

No authors report conflicts of interest.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.gaitpost.2018.06.117>.

Results: After accounting for age, stepping thresholds were, at most, moderately correlated (Pearson partial correlation coefficients $r = 0.20$ to 0.40 and $r = -0.21$ to -0.31) to several assessments of gait, postural control, and strength. Approximately 24–52% of the variance in stepping thresholds was explained by a combination of age and other fall risk assessments, which frequently consisted of balance confidence, unipedal stance time, obstacle crossing, the Romberg ratio of postural sway, and/or strength.

Significance: Our results suggest that anteroposterior fall-recovery ability, as assessed by stepping thresholds, can only be partially inferred from age and a combination of assessments of sway, strength, unipedal tasks, and balance confidence. Compensatory stepping thresholds may provide information on stability maintenance unique from other assessments of fall risk. Further investigation would be necessary to determine whether stepping thresholds are better predictors of falls in older women.

Keywords

Falls; Postural control; Gait; Balance; Aging

1. Introduction

More than 2.4 million fall injuries of older adults occur annually in the United States [1]. A goal of the Mayo Clinic Study Assessing Fall Epidemiology and Risk (*SAFER*) is to reduce fall injuries by improving risk evaluations. Recently, we developed evaluations that determine the thresholds of compensatory stepping in response to a rapid surface translation [2]. In this assessment, the anterior and posterior disturbance magnitudes that consistently elicit single- and multiple-stepping responses are identified. Although our specific protocol has not yet been related to subsequent falls, an inability to limit steps after a postural disturbance has been predictive of falls [3–5]. So, it is clear that fall-recovery performance, as evaluated by stepping thresholds, can play a meaningful role in fall-risk evaluations

The relationships between stepping thresholds and other measures of fall risk in older women are not comprehensively understood. This sex-specific approach is relevant given the influence of sex on compensatory stepping performance [6,7] and fall injury risk [1]. In a previous study of older adults, approximately 40% of the variance in waist-pull-induced, single-stepping thresholds was explained by body mass, sex, postural sway, knee extension strength, and reaction time [6]. Additional studies have found weak-to-moderate relationships between postural sway and fall-recovery performance ($|r| = 0.01$ – 0.50) [8,9]. We sought to extend these works by relating single- and multiple-stepping thresholds to assessments of postural control, gait, and strength. By doing so, we may identify established tests that are most indicative of fall-recovery performance. This aspect is important given the costs, limited accessibility, and reduced feasibility of stepping threshold assessments in clinical settings.

The purpose of this study was to quantify the relationships between established measures of fall risk and compensatory stepping thresholds in older adult women. We hypothesized that, because all measures are aimed at evaluating fall risk, established measures would significantly, but likely moderately, correlate with stepping thresholds.

2. Methods

2.1. Study participants

We recruited 125 ambulatory, community-dwelling women age 65 years or older (range: 65–91 years) for this study. Participants were active (mean $\pm$ SD caloric expenditure estimates: $27,333 \pm 6442$ kcal/week) [10] and had few comorbidities (median [I.Q.R] Charlson Comorbidity Index: 1.0 [0, 2.0]) [11]. About one third of participants (32%) reported a fall in the previous year, and 3% of participants regularly used a cane or walker. All participants, however, reported the ability to walk a city block without a gait aid. Participants had no diagnoses of dementia and were cognitively intact. Those who were not able to safely wear a harness (e.g. due to an ostomy pouch or pacemaker) or who had other reasons which the study team felt precluded safe testing (e.g. recent joint replacement) did not undergo evaluations of stepping thresholds and were excluded from this analysis. Assessments were stopped if the participant reported any pain or elected not to continue. In total, 112 participants (age = 76.6 ± 7.5 years, body mass index: 27.2 ± 4.9 kg/m²) completed at least one assessment of compensatory stepping (i.e. one of the four stepping thresholds being tested) and all other assessments of fall risk. This study was approved by the Mayo Clinic Institutional Review Board, and all participants provided written informed consent.

2.2. Fall-risk assessments

All assessments were conducted in a single session in the following order, allowing for rest in between or upon request by the participant:

1. *Balance Confidence* was recorded using the Activities-specific Balance Confidence (ABC) questionnaire [12].
2. *Gait Analysis*: Participants were outfitted with 41 retro-reflective markers affixed to their extremities, pelvis, trunk, and head. Participants walked approximately 7.5 m at a self-selected, preferred walking speed (Fig. 1A). Marker trajectories of 3–6 strides (in order to capture 6 force plate strikes, data of which are not reported here) were recorded by 10 cameras (120 Hz, Motion Analysis Corporation, Santa Rosa, CA). Kinematic variables were calculated using commercial (C-Motion Inc., Rockville, MD) and custom (Mathworks, Natick, MA) software. Outcomes included average gait speed [13], stride time [14], the percent of stride in double-support [13], and step width [15].
3. *Obstacle Crossing*: Marker-outfitted participants walked approximately 2.5 m before crossing a cylindrical foam obstacle (diameter = 2.5 cm, Fig. 1B). The outcome variable was the peak lateral speed of the whole-body center of mass (COM) during the crossing step [16]. Three trials were analyzed, each for left and right crossing-steps, and results were averaged.
4. *Standing postural sway*: Participants stood with feet placed on two force plates (Kistler Instrument Corp., Amherst, NY; Fig. 1C). Participants stood for 30 s under two conditions: first looking at a target placed 4.5 m in front of them at a height of 1.6 m, then second with eyes closed. The aggregate center of pressure (COP) was calculated from each force plate recording at 600 Hz. Outcomes

included the root-mean-square error (RMS) of the COP under eyes-closed [RMS_{EC}] and eyes-opened [RMS_{EO}] conditions, as well as the Romberg ratio of the two ($RMS_{EC/EO}$) [17].

5. *Unipedal Stance*: Participants attempted to stand on one foot for up to 30 s (Fig. 1D). The maximum time of six attempts, three on each foot, was recorded [18].
6. *Functional Reach*: Participants reached as far forward as they could with the fist of their preferred throwing hand (Fig. 1E). The average reach of the last three of five successful trials (i.e. no steps or touching of the wall) was calculated from meter-stick measures [19].
7. *Compensatory Stepping Thresholds*. All testing occurred as participants stood on a computer-controlled treadmill (ActiveStep®, Simbex, Lebanon, NH, Fig. 1G). Two progressively challenging series of disturbances were implemented [2]. One series determined anterior (ASS_{τ}) and posterior (PSS_{τ}) single-stepping thresholds. A subsequent series determined anterior (AMS_{τ}) and posterior (PMS_{τ}) multiple-stepping thresholds. Before establishing single-stepping thresholds, participants were instructed to “try not to step”. Before establishing multiple-stepping thresholds, participants were instructed to “try to take only one step”. Aside from the failure to respond as instructed, responses were also considered failures if the participant reported assistive support from the harness or the investigator observed unambiguous harness support. The disturbance that represented the threshold of interest elicited four consecutive failed responses. Thresholds were expressed as the torque (τ) necessary to counter that caused by the disturbance [2]:

$$\tau = |m \cdot a \cdot l| \quad (1)$$

where m is an individual’s mass, a is the initial disturbance acceleration, and l is the estimated whole-body COM height ($l = 0.586 \cdot \text{body height}$).

8. *Strength*: Hip, knee (Fig. 1F), and ankle flexor and extensor isometric strength of the non-dominant (i.e. non-kicking) limb was measured for three trials each (HUMAC NORM, Computer Sports Medicine, Inc., Stoughton, MA). Grip strength of each hand was individually tested three times using a dynamometer (Aeverl Medical, Gainesville, GA). The greatest force (hand grip) or torque (lower extremity) value among all trials was selected as the outcome variable for each test. In order to eliminate the influence of between-participant variability in footwear on results, participants were barefoot for assessments of gait, obstacle crossing, postural sway, and unipedal stance. Subjects wore their own well-cushioned shoes for assessments of functional reach, stepping thresholds, and strength in order to prevent injury or discomfort from rapid stepping or pushing against the dynamometer. Subjects were outfitted with a harness (Maine Anti-Gravity Systems, Inc., Portland, ME) attached to an overhead rail for assessments of gait, obstacle crossing, postural sway, unipedal stance, and stepping thresholds.

2.3. Statistical analyses

To remove the confounding influence of body size, all data were normalized to leg length and/or body mass (Table 1) [20]. Unadjusted (r) and age-adjusted (r_{adj}) Pearson correlation coefficients were calculated to determine the association of each established assessment of fall risk with stepping thresholds. To determine how established fall-risk measures explained, *in combination*, the variance in stepping thresholds, multivariable linear regression models were built. Because many of these measurements are correlated, a stepwise approach was used to select variables that explained most of the variability ($\alpha_{entry} = 0.05$, $\alpha_{removal} = 0.10$). Variable selection was further evaluated using an exhaustive best subset selection approach. Modeling assumptions, including influential points and non-normality of the residuals, were checked for the final models. All statistics were evaluated using the R software package.

3. Results

Unadjusted relationships between variables are reported in a Supplementary Material Table (Table S1), while age-adjusted correlations are presented in Table 2 and described below.

3.1. Relationships between stepping thresholds

Stepping thresholds were negatively correlated with age ($r = -0.23$ to -0.60 , Table 2). Thresholds were significantly correlated with each other ($r_{adj} = 0.29$ – 0.68), with the exception of ASS_{τ} and PMS_{τ} ($r_{adj} = 0.10$).

3.2. Relationships between gait variables and stepping thresholds

The age-adjusted relationships between gait variables and stepping thresholds were not consistent (Table 2). No gait measures were significantly correlated with ASS_{τ} ($|r_{adj}| < 0.18$), while AMS_{τ} was significantly correlated with all gait measures ($|r_{adj}| = 0.22$ – 0.34). Posterior thresholds were significantly correlated with stride width, double-limb support, and peak lateral velocity of the center of mass during obstacle crossing ($r_{adj} = -0.21$ to -0.38).

3.3. Relationships between standing postural control and stepping thresholds

Of all bipedal postural sway measures, the only significant, adjusted correlations observed with stepping thresholds were that between the Romberg ratio and single-stepping thresholds ($r_{adj} = -0.23$). A longer unipedal stance time, however, was associated with higher stepping thresholds, regardless of type ($r_{adj} = 0.25$ – 0.38). The functional reach was only significantly correlated with the AMS_{τ} ($r_{adj} = 0.21$, Table 2).

3.4. Relationships between strength and stepping thresholds

Hip extensor and flexor strength ($r_{adj} = 0.27$ – 0.40), knee extensor and flexor strength ($r_{adj} = 0.26$ – 0.37), plantarflexor strength ($r_{adj} = 0.24$ – 0.40), and grip strength ($r_{adj} = 0.20$ – 0.33) were positively correlated with all stepping thresholds following age-adjustment (Table 2). Stronger dorsiflexors were only significantly associated with higher PSS_{τ} and AMS_{τ} ($r_{adj} = 0.23$).

3.5. Relationships between balance confidence and stepping thresholds

Positive relationships between thresholds and balance confidence were observed (Table 2). Stronger relationships were apparent with multiple-stepping thresholds ($r_{adj} = 0.39\text{--}0.40$) than with single-stepping thresholds ($r_{adj} = 0.19\text{--}0.20$).

3.6. Multivariable models relating standard assessments to stepping thresholds

Approximately 25%–50% of the variance in stepping thresholds were explained by combinations of age and other assessments (Table 3). Age was the strongest contributor to multiple-stepping thresholds, but was a weaker (ASS_{τ}) or non-contributor (PSS_{τ}) to single-stepping thresholds. Four distinct trends were observed in these multivariate models. First, a single-limb stance task was included in all models. Unipedal stance time was included in both single-stepping threshold models, as well as that of AMS_{τ} (standardized $\beta = 0.25\text{--}0.31$). Peak lateral COM speed during obstacle crossing was included in both posterior thresholds (standardized $\beta = -0.21$ to -0.29). A second trend was that the Romberg ratio of postural sway was included in both single-stepping threshold models (standardized $\beta = -0.18$ to -0.19). A third trend was that strength was included as a contributor in three of the four models. Stronger plantarflexors were associated with a higher ASS_{τ} (standardized $\beta = 0.21$) and AMS_{τ} (standardized $\beta = 0.22$). Stronger hip flexors were associated with a higher PMS_{τ} (standardized $\beta = 0.14$). The fourth trend was that balance confidence was included in both multiple-stepping threshold models (standardized $\beta = 0.25\text{--}0.28$).

4. Discussion

The purpose of this study was to quantify the relationships between established measures of fall risk and compensatory stepping thresholds in older adult women. We hypothesized that established measures would significantly, but likely moderately, correlate with stepping thresholds. This hypothesis was partially supported. Age-adjusted correlations between stepping thresholds and other assessments of gait, standing postural control, strength, and balance confidence were, at most, moderate ($|r_{adj}| \leq 0.40$), suggesting that stepping thresholds may provide information on stability maintenance that is unique from that of these other measures. The multivariate models produced in this study (adjusted $R^2 = 0.24\text{--}0.52$) suggest that a combination of age, balance confidence, strength, and other assessments of standing sway, unipedal stance, and/or obstacle crossing partially capture the ability to arrest a fall. Further evaluation of stepping thresholds is needed to determine whether their unique qualities improve prediction of falls in the community.

The lack of consistent associations *between* types of stepping thresholds suggests that fall-recovery ability is not a general characteristic of an individual. Fall direction (anterior vs posterior) and constraints on stepping appear to be important considerations. Anterior and posterior multiple-stepping thresholds held the strongest between-threshold relationship, suggesting that the stepping skill may be generalizable across fall directions. What was surprising was the weaker relationships exhibited between the ASS_{τ} and other stepping thresholds ($r_{adj} = 0.10\text{--}0.37$). Given that anterior single-stepping thresholds do not have a prospective relationship with falls [4], the relevance of the ASS_{τ} measure is questionable.

Our results do not support gait speed as being indicative of fall-recovery ability, despite its documented relationship to falls [13]. Not surprisingly, given that both tasks consist of forward steps, all steady-state gait kinematics held significant correlations with AMS_{τ} (Table 2). These relationships, however, did not all persist when evaluating correlations with other stepping thresholds. Of note, the gait kinematics most logically associated with stability (stride width and double-limb support) persisted in having significant correlations with posterior thresholds (Table 2).

Previously reported models of anterior single-stepping thresholds identified postural sway with eyes open on a foam surface as a predictor [6]. This is a condition where somatosensation is altered and the individual must rely more on vision and the vestibular system for control. In contrast, our analyses identified the Romberg ratio as being related to single-stepping thresholds (Tables 2 and 3). A higher ratio suggests that an individual relies more on vision for postural control, potentially due to impaired lower-extremity somatosensation. Individuals with impaired somatosensation, such as neuropathy patients, have a delayed muscle response to postural disturbances [21]. Vibration sense has explained 31% of the variance in anterior single-stepping thresholds [22]. Given this evidence, somatosensation likely plays an important role in the single-stepping threshold measures. From our results and others [8,9], such control of standing posture is not reflective of fall-recovery with a step.

Our results suggest that strength contributes to fall-recovery ability. It is likely that plantarflexor weakness impairs the efficacy of the “ankle strategy” [23] response, as suggested by plantarflexor strength’s inclusion in our ASS_{τ} model (Table 3) and its stronger relationships with anterior thresholds over posterior thresholds (Table 2). A previous study focused on anterior responses found that plantarflexor, knee extensor, and hip flexor weakness were associated with taking multiple steps [24]. Given that plantarflexor strength exhibited the strongest strength-related correlations with anterior thresholds (Tables 2 and 3), we believe that this strength measure is the most relevant to forward fall recovery. This evidence is in agreement with the proposed role of the stance-limb plantarflexors in reducing rotational momentum and increasing step length [7]. The inclusion of hip flexor strength in the PMS_{τ} model, albeit relatively weak compared to that of other independent variables (Table 3), suggests that this muscle group could play a similar role during backward falls. Of note, grip strength was also positively associated with stepping thresholds (Table 2). While grip strength is not as strongly predictive of falls as lower-extremity measures [25], it can be assessed at less cost and greater feasibility.

Both previously reported [6] and our multivariate models to predict posterior single-stepping thresholds did not include direct measures of strength. Instead, previous studies identified reaction time as a predictor [6]. Although reaction time is an important aspect to fall recovery, we did not include a direct measure of it in our study. Instead, our multivariate models identified unipedal stance time as a predictor. Of all standing postural control measures, unipedal stance had the strongest correlations with age and stepping thresholds (Table 2). Older adults often fail to maintain unipedal stance within the first five seconds, demonstrating greater kinetic variability during this time than younger counterparts [26]. Indeed, 29% of our subjects failed to maintain unipedal stance for more than 5 s. Reaction

time likely mediates the rapid adjustments necessary for initiating and maintaining unipedal stance, and therefore may underlie the relationships between unipedal stance and single-stepping thresholds.

Unipedal stance or the lateral speed of the whole body COM during obstacle crossing were selected in multiple-stepping threshold regression models (Table 3). Notably, these measures had the strongest correlations with stepping thresholds of all gait and standing postural control measures (Table 2). Unipedal stance, obstacle crossing, and compensatory stepping all involve a limited base of support with likely the most frontal plane momentum of all assessments studied. Elderly adults with balance disorders have difficulty minimizing lateral motion during obstacle crossing [16]. Rapid compensatory steps involve lateral motion due to a limited postural adjustment before the step, and older adult fallers demonstrate different frontal plane kinematics during recovery steps [27]. So, it is likely that frontal-plane kinematics are important determinants of the single-stepping response.

Balance confidence was positively correlated with all stepping threshold measures (Table 2). Based on standardized coefficients, measures which reflect the relative strength of independent variable effects on the dependent variable, balance confidence was the most influential balance measure in predicting multiple-stepping thresholds (Table 3). Balance confidence has demonstrated significant correlations with volitional step length and rapid stepping performance [28]. Poor confidence may be the result of an impaired stepping ability. Conversely, lower stepping thresholds may be the result of little confidence in maintaining stability after the first step. When compared directly to rapid volitional stepping, the ABC does a poorer job of differentiating fallers from non-fallers [29]. Therefore, stepping may be the more appropriate intervention target as a means to reduce falls.

Our results are limited to community-dwelling women with few mobility limitations. Unlike previous studies [7,24], we found an age-related decline in stepping threshold performance (Table 2). Future studies are needed to understand these relationships in other populations, such as older men. Notably, older women have exhibited worse stepping threshold performance compared to that of men [6,24]. Relationships with lateral perturbations, which are relevant to fall risk [3], should also be explored.

Overall, we found that, after accounting for age, tests of balance confidence, unipedal stance, obstacle crossing, and strength were the best predictors of stepping thresholds. However, these measures only reflect a portion of an older woman's fall-recovery performance as evaluated by stepping thresholds. Our results warrant further investigation of the relationship between stepping thresholds and falls experienced in the community.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.

The gait (A), obstacle crossing (B), standing postural sway (C), unipedal stance (D), functional reach (E), and isometric strength (F) of all participants was assessed in this study. Additionally, participants responded to anterior and posterior disturbances from a treadmill (G). Two series of progressive disturbances were implemented in order to determine anterior and posterior single-stepping and multiple-stepping thresholds.

Table 1

Normalization techniques for all variables.

Variable		Units	Normalization
Stepping Thresholds	ASS _τ	N·m	$(mass \times leg \times g)^{-1}$
	PSS _τ	N·m	
	AMS _τ	N·m	
	PMS _τ	N·m	
Gait Variables	Speed	m/s	$(\sqrt{g \times leg})^{-1}$
	Stride Width	m	$(leg)^{-1}$
	Stride Time	s	$(\sqrt{leg/g})^{-1}$
	Double-limb Support	% stride	–
	Obstacle Crossing:	m/s	$(\sqrt{g \times leg})^{-1}$
	Peak Lateral COM		
	Speed		
Standing Postural Control	RMS _{EO}	m	$(leg)^{-1}$
	RMS _{EC}	m	$(leg)^{-1}$
	RMS _{EC/EO}	–	–
	Unipedal Stance	s	$(\sqrt{leg/g})^{-1}$
	Functional Reach	m	$(leg)^{-1}$
Isometric Strength	Plantarflexor	N·M	$(mass \times leg \times g)^{-1}$
	Dorsiflexor	N·m	
	Knee Extensor	N·m	
	Knee Flexor	N·m	
	Hip Extensor	N·m	
	Hip Flexor	N·m	
	Grip	kg	$(mass)^{-1}$
Balance Confidence (ABC)		%	–

Note: *leg* is leg length (trochanteric height of the non-kicking limb), mass is body mass, and *g* is gravity (9.81 m/s²). Normalizations follow previous recommendations for scaling gait variables [20] Abbreviations: Anterior (A), Posterior (P), Single-Stepping (SS), and Multiple-Stepping (MS) thresholds. Root Mean Square error (RMS) of the center of pressure with eyes closed (EC), eyes opened (EO), or the ratio of the two (Romberg Ratio = EC/EO). Activities-Specific Balance Confidence (ABC).

Pearson correlation coefficients between outcome measures and age, as well as Pearson partial correlation coefficients between stepping thresholds and other measures, adjusted for age.

Table 2

Outcome Measure	Mean ± S.D.	Age (years)				Stepping Thresholds			
			ASS τ	PSS τ	AMS τ	PMs τ			
Stepping Thresholds	ASS τ	0.33 ± 0.08	–	–	0.29 ^{***}	0.37 ^{***}	0.10		
	PSS τ	0.27 ± 0.07	0.29 ^{**}	–	–	0.46 ^{***}	0.53 ^{***}		
	AMS τ	0.90 ± 0.24	0.37 ^{***}	0.46 ^{***}	–	–	0.68 ^{***}		
	PMs τ	0.51 ± 0.15	0.10	0.53 ^{***}	0.68 ^{***}	–	–		
Gait Variables	Speed	0.36 ± 0.07	0.17	0.17	0.24 [*]	0.15			
	Stride Width	0.11 ± 0.04	–0.08	–0.29 ^{**}	–0.31 ^{**}	–0.31 ^{**}	–0.31 ^{**}		
	Stride Time	3.61 ± 0.34	–0.14	–0.08	–0.22 [*]	–0.13			
	Double-Limb Support	26.8 ± 4.5	–0.14	–0.21 [*]	–0.31 ^{**}	–0.21 [*]			
	Obstacle Crossing: Peak Lateral COM Speed	0.05 ± 0.01	–0.18	–0.38 ^{***}	–0.34 ^{***}	–0.38 ^{***}			
	RMS _{EO}	0.07 ± 0.03	–0.01	0.06	–0.12	–0.07			
Standing Postural Control	RMS _{EC}	0.07 ± 0.02	–0.16	–0.12	–0.16	–0.04			
	RMS _{EC/EO}	1.00 ± 0.27	–0.23 [*]	–0.23 [*]	–0.03	0.05			
	Unipedal Stance	48.1 ± 33.2	0.30 ^{**}	0.34 ^{***}	0.38 ^{***}	0.25 ^{**}			
Isometric Strength	Functional Reach	0.30 ± 0.09	0.13	0.12	0.21 [*]	0.13			
	Plantarflexion	0.11 ± 0.05	0.31 ^{**}	0.29 ^{**}	0.40 ^{***}	0.24 [*]			
	Dorsiflexion	0.03 ± 0.01	0.18	0.23 [*]	0.23 [*]	0.11			
	Knee Extension	0.16 ± 0.06	0.28 ^{**}	0.34 ^{***}	0.37 ^{***}	0.30 ^{**}			
	Knee Flexion	0.06 ± 0.02	0.26 ^{**}	0.28 ^{**}	0.32 ^{**}	0.28 ^{**}			
	Hip Extension	0.11 ± 0.05	0.27 ^{**}	0.28 ^{**}	0.40 ^{***}	0.34 ^{***}			
	Hip Flexion	0.11 ± 0.04	0.31 ^{**}	0.32 ^{**}	0.40 ^{***}	0.34 ^{***}			
	Grip	0.36 ± 0.10	0.26 ^{**}	0.24 [*]	0.33 ^{**}	0.20 [*]			
	Balance Confidence (ABC; %)	88.1 ± 11.4	0.19 [*]	0.20 [*]	0.39 ^{***}	0.40 ^{***}			

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Note: All measures were normalized to body size (Table 1). Significant correlations are marked with an asterisks depending on alpha level

*
**

p = 0.05
p = 0.01
p = 0.001

Abbreviations: Anterior (A), Posterior (P), Single-Stepping (SS), and Multiple-Stepping (MS) thresholds. Root Mean Square error (RMS) of the center of pressure with eyes closed (EC), eyes opened (EO), or the ratio of the two (Romberg Ratio = EC/EO). Activities-Specific Balance Confidence (ABC).

Table 3

Multivariate regression models to predict stepping thresholds.

Dependent Variable	Independent Variables	Unstandardized Coefficients		Standardized Coefficients		p-value
		β	Std. Error	β		
ASS _τ (adj- R^2 = 0.24, n = 112)	Constant	0.48	0.10			< 0.001
	Age (years)	-0.0021	0.0011	-0.19		0.071
	RMS _{EC/EO}	-0.059	0.025	-0.19		0.023
	Unipedal Stance	0.00061	0.00027	0.25		0.024
	Plantarflexor Strength	0.36	0.15	0.21		0.017
PSS _τ (adj- R^2 = 0.26, n = 112)	Constant	0.36	0.034			< 0.001
	OC L COM speed	-1.49	0.44	-0.29		< 0.001
	RMS _{EC/EO}	-0.044	0.020	-0.18		0.034
	Unipedal Stance	0.00061	0.00017	0.31		< 0.001
	Constant	0.89	0.31			0.005
AMS _τ (adj- R^2 = 0.48, n = 102)	Age (years)	-0.0094	0.0030	-0.30		0.002
	Unipedal Stance	0.0019	0.00069	0.26		0.008
	Plantarflexor Strength	1.12	0.41	0.22		0.007
	Balance Confidence (ABC, %)	0.0058	0.0017	0.28		< 0.001
	Constant	1.00	0.18			< 0.001
PMS _τ (adj- R^2 = 0.52, n = 105)	Age (years)	-0.0095	0.0015	-0.47		< 0.001
	OC L COM speed	-2.7	0.92	-0.21		0.005
	Hip Flexor Strength	0.63	0.33	0.14		0.057
	Balance Confidence (ABC, %)	0.0034	0.0011	0.25		0.002
	Constant					

Note: All measures were normalized to body size (Table 1). Stepping thresholds (τ) include Anterior (A), Posterior (P), Single-Stepping (SS), and Multiple-Stepping (MS) thresholds. "OC L COM speed" is the peak lateral speed of the whole-body center of mass during obstacle crossing. RMSEC/EO is the ratio of the center of pressure root mean square error between eyes-closed and eyes-opened conditions (i.e. Romberg Ratio [17,30]). ABC is the Activities-Specific Balance Confidence scale [12].